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The Codisposal of Sewage Sludge and Refuse in the PUROX System

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This program was conducted to establish the technical feasibility of codisposal of filtered sludge cake from primary and secondary wastewater treatment with municipal refuse in the PUROX System; to determine the environmental effect of this process; and to estimate the economics of sludge disposal in this fashion. At the PUROX System demonstration plant in South Charleston, West Virginia, operation at dry sludge-to-refuse ratios up to 0.075 was obtained. System performance was similar to that obtained with refuse only. Environmental effects were within Federal guidelines for emissions. Economics were found to be strongly influenced by site-specific factors with sludge disposal costs varying from less than $20 per Mg to above $100 per Mg of dry sludge.

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THE CODISPOSAL OF SEWAGE SLUDGE AND REFUSE IN THE PUROX SYSTEM

by

Union Carbide Corporation
Linde Division
Tonawanda, New York 14150

Grant No. S803769-01-3

Project Officer

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This study was conducted
in cooperation with the
Sanitary Board of the City of
South Charleston, West Virginia

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The codisposal of sewage sludge and municipal refuse in an environmentally sound fashion provides a synergistic solution to a difficult waste disposal problem with the added benefit of energy recovery that has previously been lost. In light of current environmental concerns and energy limitations new technologies such as reported here have taken on increased significance.

Francis T. Mayo, Director
Municipal Environmental Research
Laboratory

ABSTRACT

This test program was conducted with three overall objectives:

1. To establish the technical feasibility of codisposal of filtered municipal sewage sludge of various types with mixed municipal refuse in the PUROX System.
2. To determine the environmental effect of such a codisposal process.
3. To estimate the economic advantage of this codisposal process.

The PUROX System demonstration plant in South Charleston, West Virginia was modified to mix filtered sewage sludge cake with shredded, magnetically separated refuse prior to feeding into the PUROX System. The modified system included the standard PUROX System equipment: a shredder, magnetic separator, oxygen blown converter, slag quench tank, offgas scrubber, electrostatic precipitator, condenser and product gas combustor. A sludge receiving and storage station, a metering hopper, and a transfer conveyor were added to provide the sludge processing capability. Raw primary sludge filter cake with 25 percent solids and mixed primary and secondary sludges (mixed sludge) filter cake with 20 percent solids were processed. In the process the refuse/sludge mixture was dried, pyrolyzed, combusted, and the inorganic residue was slagged to produce a fuel gas, an environmentally inert slag, and a wastewater stream.

Results of the tests indicate that sludge can be processed with refuse in an efficient, environmentally sound manner. System performance at dry-sludge to refuse ratios up to 0.075 was excellent. Values for key operating variables such as oxygen consumption, gas production, and gas heating value were within the range of variation experienced with refuse only. Use of 80 percent moisture sludges in the composition range studied resulted in no significant variation in overall performance. Although maximum operating capacity was not tested due to the limited supply of refuse, the substitution of wet sludge for refuse on a unit-for-unit basis should not affect the total operating rate when defined as total units per day fed. Clearly, the yield of product gas per unit of material fed will decrease at higher moisture levels. To process higher dry sludge-to-refuse ratios, minor modifications of the refuse-sludge blending operation may be required.

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The effect of effluent streams from the process on the environment falls well within Federal guidelines for emissions. Heavy metals found in both the sludge and refuse were effectively contained in the slag. Samples of slag were tested for leachability, and results of the tests indicated no significant leaching from the slag. The particulate content of the product gas presents no apparent problem when compared to regulations on emissions from a stationary source. Bench scale treatability studies of wastewater during this program and previous studies with refuse-only indicate that PUROX System wastewater can be treated to municipal sewer discharge standards.

The economics of this codisposal process are very sensitive to the dry sludge-to-refuse ratio, sludge moisture content, and overall facility size. The estimated net sludge disposal cost for processing 63.5 dry Mg (70 dry tons) per day of sludge at a sludge (dry solids) to refuse ratio of 0.05 is approximately $110 per dry Mg ($100 per dry ton) using the basic process as reported here. A modification of the process to provide improved filtration of sludge and predrying of sludge filter cake can result in a reduction in the estimated sludge disposal cost by 80 percent to approximately $22 per dry Mg ($20 per dry ton).

This report was submitted in fulfillment of Grant #S-803769 by Union Carbide Corporation under the sponsorship of the Sanitary Board of the City of South Charleston, West Virginia and the U. S. Environmental Protection Agency. This report covers the period June 24, 1975 to June 16, 1977 and work was completed as of January, 1978.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

Btu -- British thermal unit
C -- Celsius
d -- day
ft -- foot
ft^3 -- cubic feet
F -- Fahrenheit
gal -- gallon
gr -- grain
g -- gram
GJ -- Gigajoule = 10^9 Joules
HHV -- Higher heating value
hr -- hour
I -- Isokinetic variation (%)
J -- Joule
kg -- kilogram
kJ -- kilojoule = 10^3 Joules
kw -- kilowatt
lb -- pound
m -- meter
m^3 -- cubic meter
mg -- milligram = 10^{-3} grams
Mg -- Megagram = 10^6 grams
μg -- Micrograms = 10^{-6} grams
MJ -- Megajoule = 10^6 Joules
MLVSS -- Mixed liquor volatile suspended solids
Nm^3 -- Normal cubic meter at 0 degrees C, 1 atm
Pa -- Pascal (pressure)
pH -- Negative logarithm of hydrogen ion concentration
psig -- pound per square inch gage
Sft^3 -- Standard cubic feet at 60 degrees F, 1 atm
$SBOD_5$ -- Soluble biological oxygen demand
SCOD -- Soluble chemical oxygen demand
S_e -- wastewater reactor effluent
S_o -- wastewater reactor input
$TBOD_5$ -- Total biological oxygen demand
TCOD -- Total chemical oxygen demand
t_d -- Retention time

LIST OF ABBREVIATIONS AND SYMBOLS (continued)

SYMBOLS

Ag -- Silver
Ar -- Argon
As -- Arsenic
Au -- Gold
Al_2O_3 -- Alumina
Ba -- Barium
BaO -- Barium oxide
Be -- Beryllium
C -- Carbon
Cd -- Cadmium
Cr -- Chromium
Cu -- Copper
CaO -- Calcium oxide
Cr_2O_3 -- Chromic oxide
Cl -- Chlorine
CH_4 -- Methane
CH_3OH -- Methanol
C_2H_2 -- Acetylene
CH_3COOH Acetic acid
C_2H_4 -- Ethylene
C_2H_6 -- Ethane
C_3H_6 -- Propylene
C_3H_8 -- Propane
C_6H_6 -- Benzene
CO -- Carbon monoxide
CO_2 -- Carbon dioxide
F -- Fluorine
Fe -- Iron
FeO -- Iron oxide

H -- Hydrogen (atomic)
HCl -- Hydrochloric acid
HF -- Hydrofluoric acid
H_2 -- Hydrogen (molecular)
HNO_3 -- Nitric acid
H_2S -- Hydrogen sulfide
H_2SO_4 -- Sulfuric acid
Hg -- Mercury
KI -- Potassium Iodide
$KMnO_4$ -- Potassium permanganate
MgO -- Magnesium oxide
Mn -- Manganese
MnO -- Manganese oxide
NaOH -- Sodium hydroxide
Ni -- Nickel
NiO -- Nickel oxide
O -- Oxygen (atomic)
O_2 -- Oxygen (molecular)
P -- Phosphorus
P_2O_5 -- Phosphorus pentoxide
Pb -- Lead
Pt -- Platinium
SiO_2 -- Silicon dioxide
SO_2 -- Sulfur dioxide
SO_3 -- Sulfur trioxide
TiO_2 -- Titanium dioxide
TLV -- Threshold level value
TWA -- Time weighted average
Zn -- Zinc

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Finally, the cooperation and guidance provided by Mr. Gerald Stern, Project Officer, and Dr. J. B. Farrell, Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency are acknowledged.

SECTION 1

INTRODUCTION

The disposal of waste materials in an environmentally sound fashion has been a major concern for many years. In view of the increasing scarcity of energy, the disposal of waste materials such as mixed municipal refuse and sewage sludge by the conventional techniques of landfilling or incineration represents both a waste of valuable energy resource and an environmental hazard. The PUROX System has been developed as an environmentally acceptable conversion technology for the recovery of usable energy from solid waste materials. The key element in this process is the converter which is an oxygen-blown shaft furnace in which the solid waste materials are dried, pyrolyzed, combusted, and the inorganic residues slagged. The use of oxygen in the converter results in a very small gas volume to be cleaned, low exhaust gas temperatures from the converter, minimum dilution of the fuel gas with nitrogen, and maximum consolidation of inorganics in the residue. This consolidation is a result of the high temperature slagging conditions in the hearth of the converter. The conversion process produces a useful fuel gas, wastewater and an inert slag stream. The operation is supported by several subsystems: a feed material storage and preparation system, a gas cleaning system, a wastewater treatment system, and an oxygen generating system, and utilities and services.

The codisposal of sewage sludge and refuse in the PUROX System is viewed as desirable for several reasons:

(a) Codisposal of refuse and sewage sludge permits disposal of sludge and refuse with a net production rather than a net consumption of energy as in conventional incineration techniques.

(b) The refuse bed in the shaft furnace provides efficient heat transfer from ascending gas to dry the solids prior to pyrolysis and combustion as well as acting as an effective heat sink to cool the exhaust gas to a low temperature before it exits from the converter. This low exhaust temperature ensures that no significant amount of heavy metals will be present as vapor in the gas stream.

(c) The glassy slag from the refuse provides an ideal matrix in which the trace metal contaminants from the sludge are trapped by physicochemical bonding in the silicate matrix of the slag.

This program was devised to investigate the overall technical feasibility and environmental effect of this new concept for disposing of sludge with refuse in a slagging system. The economics of conducting this codisposal process on a commercial scale are also briefly discussed.

SECTION 2

CONCLUSIONS

The codisposal of both raw primary and mixed primary and secondary sewage sludge (mixed sludge) filter cake with municipal refuse in the PUROX System has been demonstrated during a 64 day test period of 24 hour per day operation. Over the range of feed compositions investigated, (0.024 to 0.074 sludge dry solids to refuse), sludge was dried, pyrolyzed, combusted, and slagged in combination with municipal refuse in the PUROX System to produce a useful fuel-gas, an environmentally inert slag, and wastewater which could be treated to acceptable discharge standards.

Of particular interest is the deposition of heavy metals in the process streams leaving the PUROX System. Projecting the actual test results to include particulate recycle (not tested with refuse-sludge mixtures because of mechanical problems in the recycle stream) it is projected that only Hg, Zn and Pb would show less than 90% retention in the inert slag (however, over 75% of these three elements would end up in the slag). The gas-cleaning system is, however, known to be effective for removing these elements.

The environmental effect of this codisposal technique appeared to fall well within federal guidelines for environmental emissions. The capture of heavy metals in a non-leachable form in the slag as well as the recovery of a large portion of the sludge heating value makes the use of this technique particularly attractive.

A projection of the economics of commercially applying this process shows a strong sensitivity to sludge moisture content, refuse-to-sludge ratio, and overall facility size. The economics of the process are closely tied to case-specific factors particularly the allowable refuse tipping fee. At the dry sludge-to-refuse ratio of 0.05, a net sludge disposal cost of about $110 per dry Mg ($100 per dry ton) of sludge is projected based on a refuse tipping fee of $14.30/Mg ($13 per ton) utilizing a codisposal plant processing 63.5 dry Mg (70 dry tons) per day of sludge and 1270 Mg (1400 tons) per day of refuse.

At a sludge (dry solids) to refuse ratio of 0.074 using 23% solids raw primary sludge cake, one Mg (0.91 ton) of refuse/sludge mixture could be converted to 0.59 Mg (0.53 ton) of product gas, 0.19 Mg (0.17 ton) of slag, and 0.43 Mg (0.39 ton) of wastewater using 0.21 Mg (0.19 ton) of oxygen.

Over the range of feed compositions studied, the system performance parameters in the codisposal mode were quite similar to the performance processing refuse alone. Oxygen consumption and offgas quality were both within the range of variation observed with refuse alone. Based on measured values, the overall conversion of the energy in the feed material to useful gas in the 12.8 - 14.8 MJ/Nm^3 (325 - 375 Btu/Sft^3) range is expected to exceed 70 percent when the particulate streams are recycled.

At the lowest sludge solids content (high moisture sludge), the blending of the sludge and refuse was not uniform. Equipment specified for this task requires careful selection to ensure proper operation of the PUROX System if sludge moisture contents greater than 75% are to be used. Equipment changes from that described here would be required to process less than 25 percent solids material.

Mechanical problems with the particulate recycle system prevented collection of a complete set of representative samples during the tests. However, additional internal stream samples were collected to permit the complete evaluation of the operation and to allow reasonable projections from the actual operating conditions to design operating conditions. Subsequent to the codisposal tests, data was collected with the particulate recycle system operating while processing refuse only. This data supports the reasonableness of these projections.

SECTION 3

RECOMMENDATIONS

Codisposal of sewage sludge and refuse in the PUROX System should continue to be evaluated. Follow-on studies should be conducted to evaluate alternate sludge/refuse blending devices which would permit operation at higher sludge-to-refuse ratios. The feasibility of integrating the wastewater treatment and refuse disposal facilities should be examined.

The low dry sludge-to-refuse ratios investigated in this study are appropriate to meet the needs of municipalities with relatively small amounts of sludge to dispose of and high allowable refuse disposal costs. For communities with larger amounts of sludge and less favorable allowable refuse disposal costs, higher ratios of dry sludge-to-refuse are appropriate. Combination of these higher ratios with integration of refuse processing and wastewater treatment plant warrants study. Codewatering of sludge and slurry from the scrubber may significantly reduce costs over separate filtration. Similarly, predrying the char/sludge filter cake prior to charging into the PUROX System converter should provide economical and efficient utilization of oxygen within the PUROX System and hence reduce overall sludge disposal costs.

SECTION 4

PUROX SYSTEM FACILITY PROCESS DESCRIPTION

The PUROX System codisposal facility as designed by Union Carbide consists of the following components: a front end refuse receiving and preparation system, a PUROX System consisting of, but not limited to a refuse gasifying converter, an offgas cleaning system, and auxiliary systems including oxygen generating, wastewater treatment, and product gas handling systems. Figures 1 and 2 present typical mass and energy balances on the 181 Mg (200 ton) per day demonstration plant in South Charleston, West Virginia. Figures 3-11 present photographs of the operating system.

Processing of refuse begins in the refuse receiving and storage building. (Figure 3). This building provides one day's inventory of refuse at the system's rated capacity. Refuse is brought to the plant in conventional packer trucks and discharged directly onto the building floor (Figures 4 and 5). A front loader manages the refuse inventory and loads refuse into the conveying system for processing.

The front loader holds about 1.1 Mg (one ton) of refuse in its bucket, carries the refuse to a scale for weighing, and discharges the refuse into the processing system (Figure 6). The refuse entering the process has a composition similar to that listed in Tables 1 and 2. Refuse is dumped onto an apron conveyor for transport to a shredder (Figure 7). The shredder rated at 13.6 Mg (15 tons) per hour shredding capacity has significant overcapacity to allow for mechanical problems in the feed system and downtime for routine shredder maintenance (Figure 8).

Shredded refuse is discharged to a high speed belt conveyor for transport to the feed conveyor. This refuse passes under a drum magnetic separator where ferrous metals are removed and discharged onto a third conveyor (Figure 9). The magnetically separated refuse drops from the belt conveyor onto the feed conveyor to the feeder. The refuse feeder forms the shredded refuse into pellets and introduces them into the converter. These pellets while in the feeder provide a gas seal for the converter.

In the converter the refuse is contacted countercurrently with hot gases from combustion in the hearth; in the upper portion of the converter free

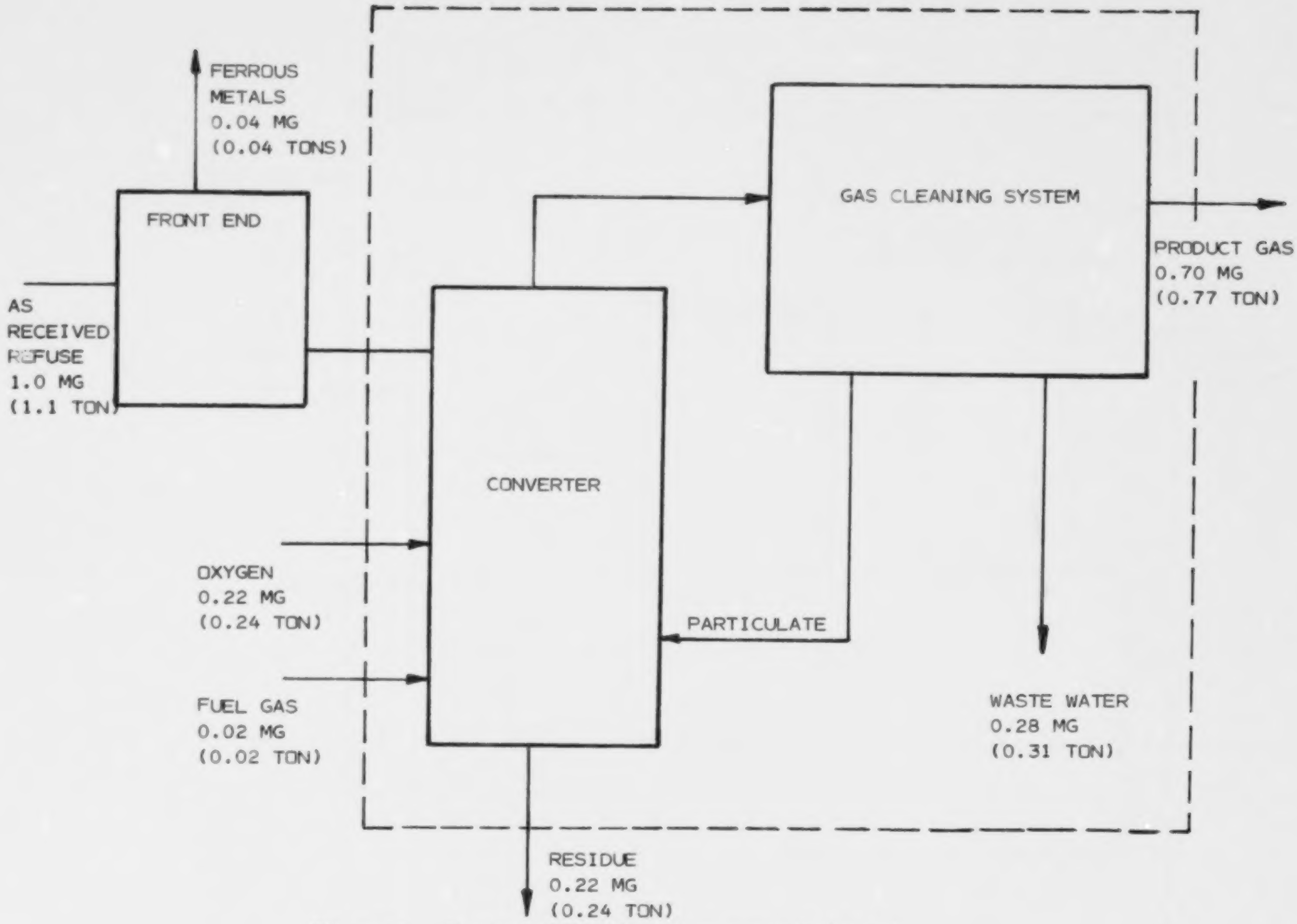

Figure 1. Typical PUROX system mass balance.

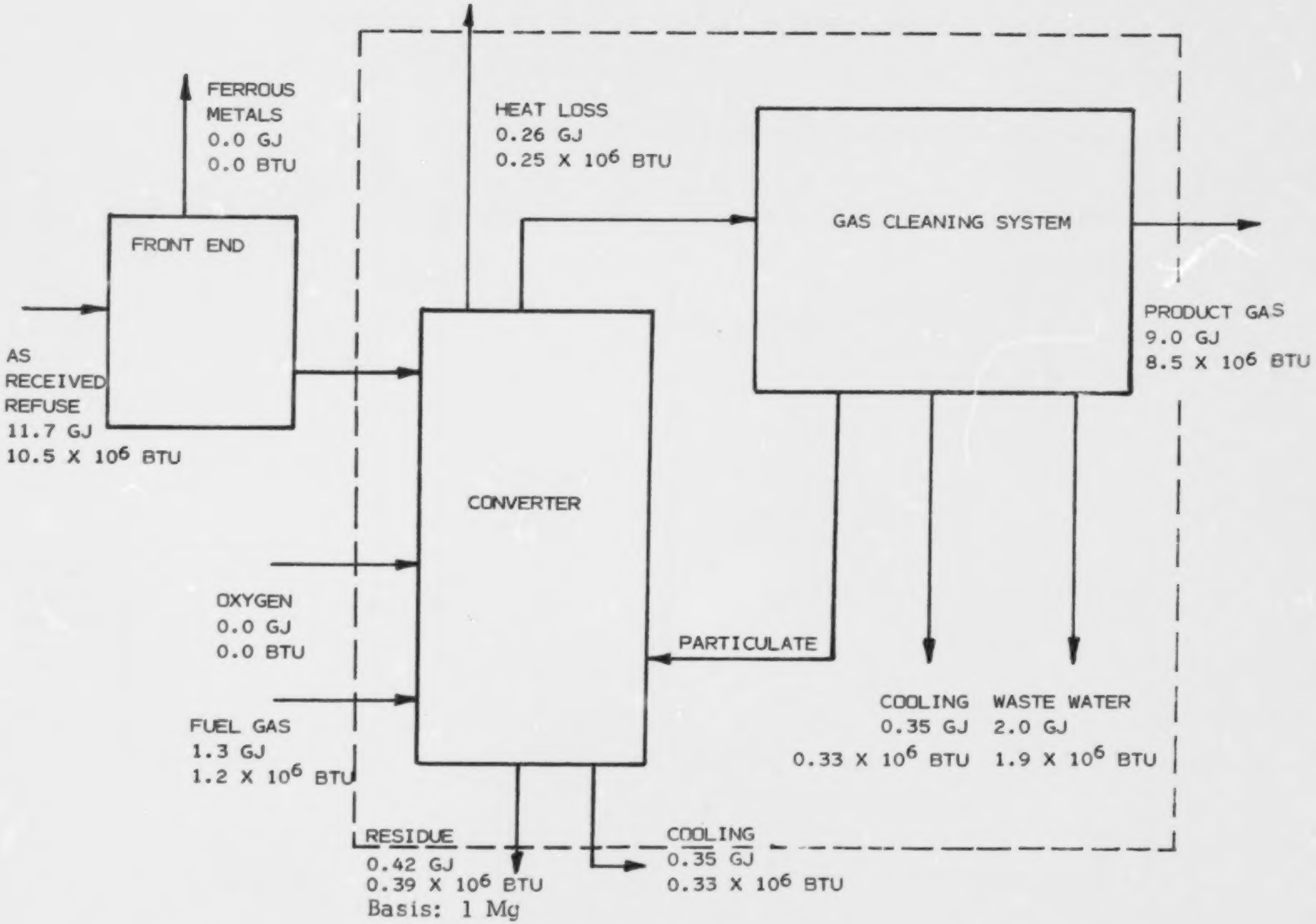

Figure 2. Typical PUROX system energy balance.

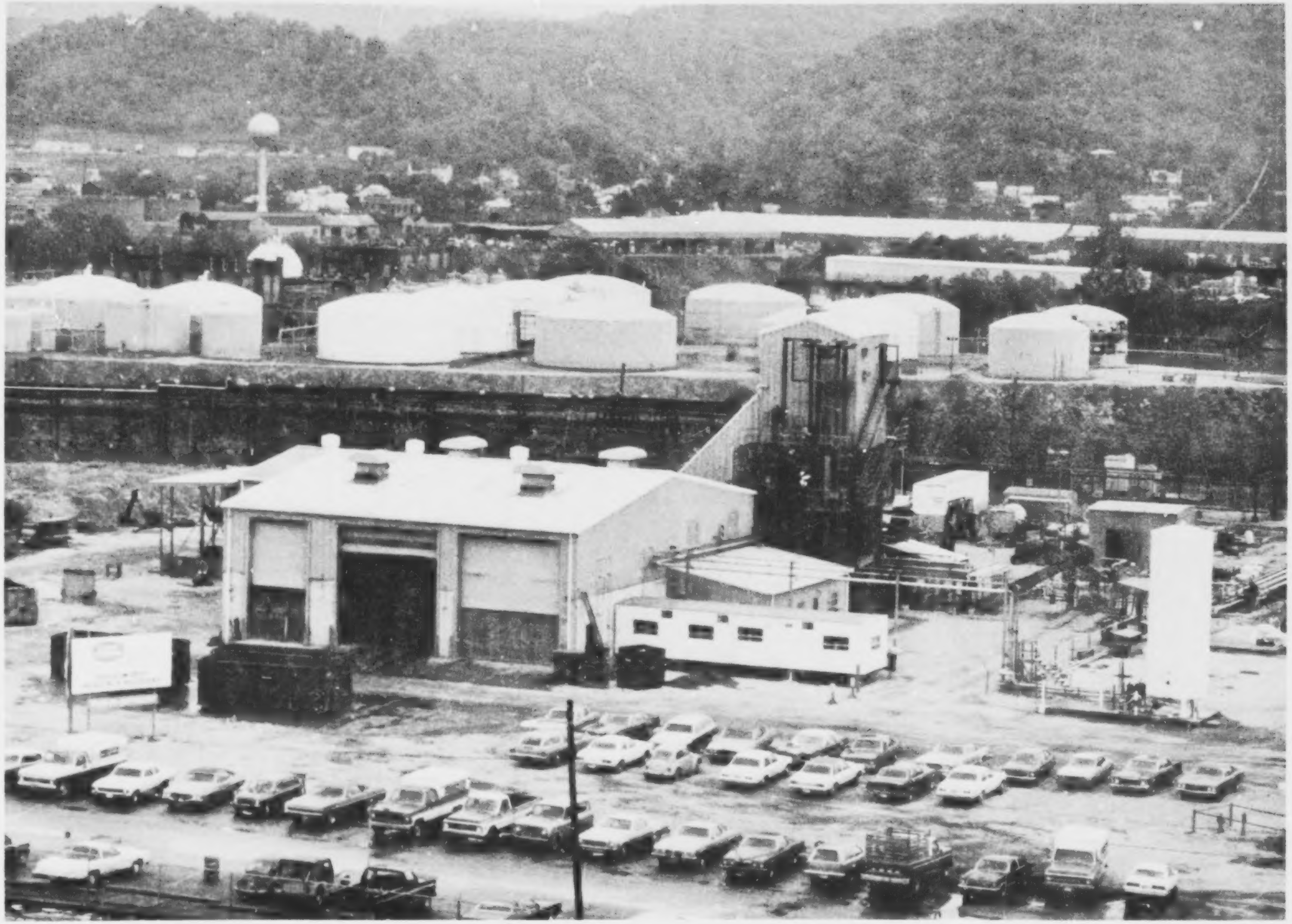

Figure 3. PUROX system facility S. Charleston, West Virginia.

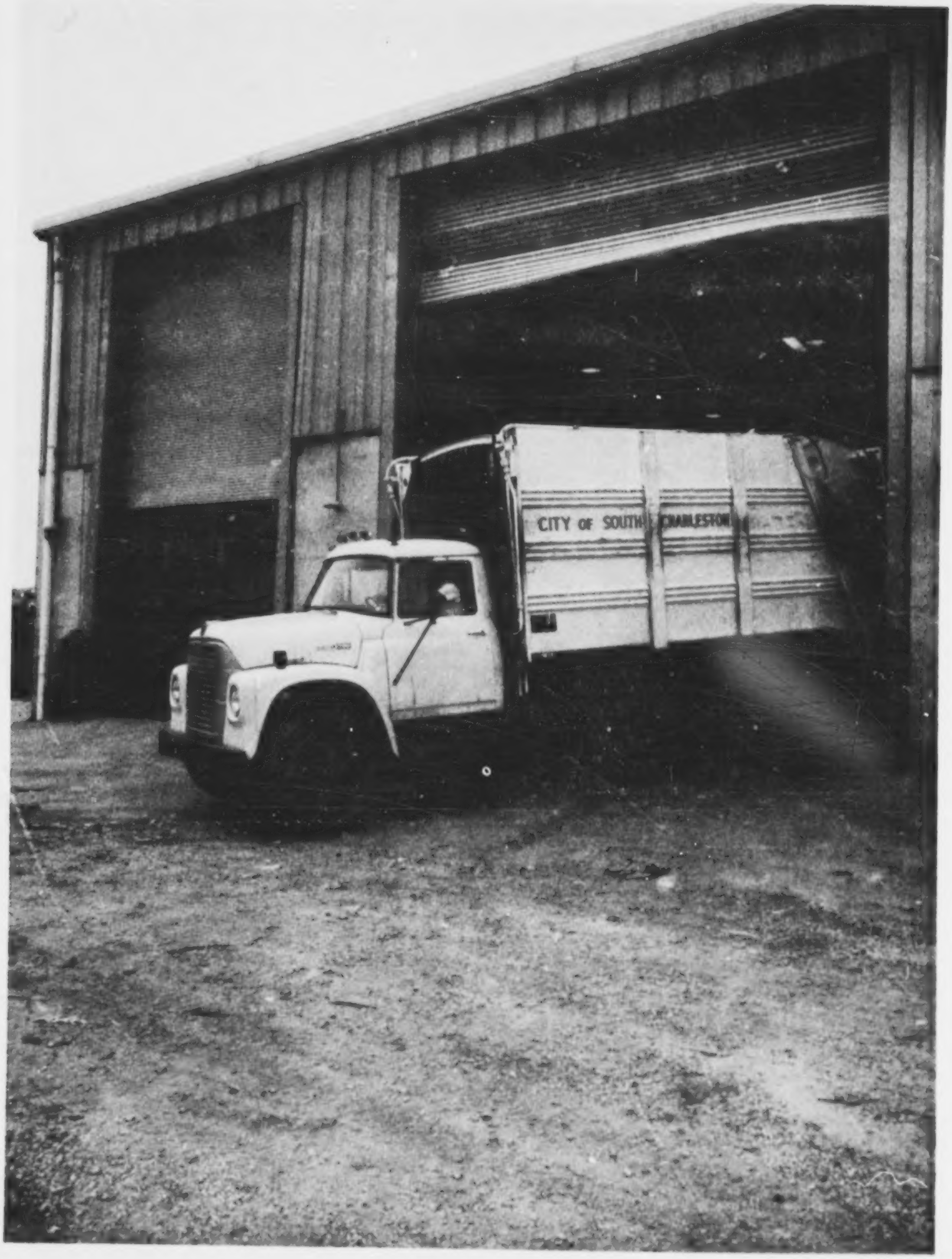

Figure 4. Packer truck delivering refuse.

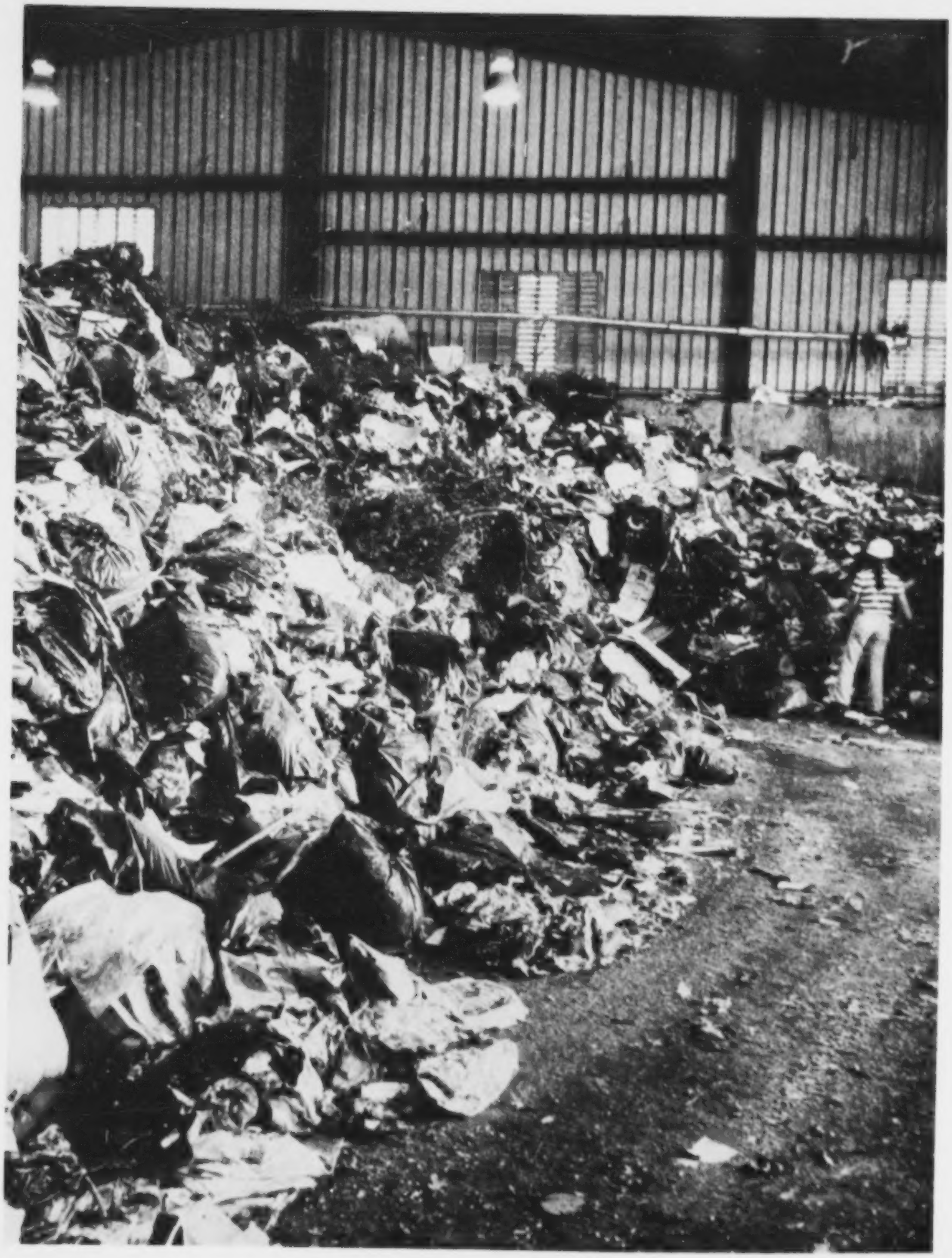

Figure 5. Refuse inventory in storage building.

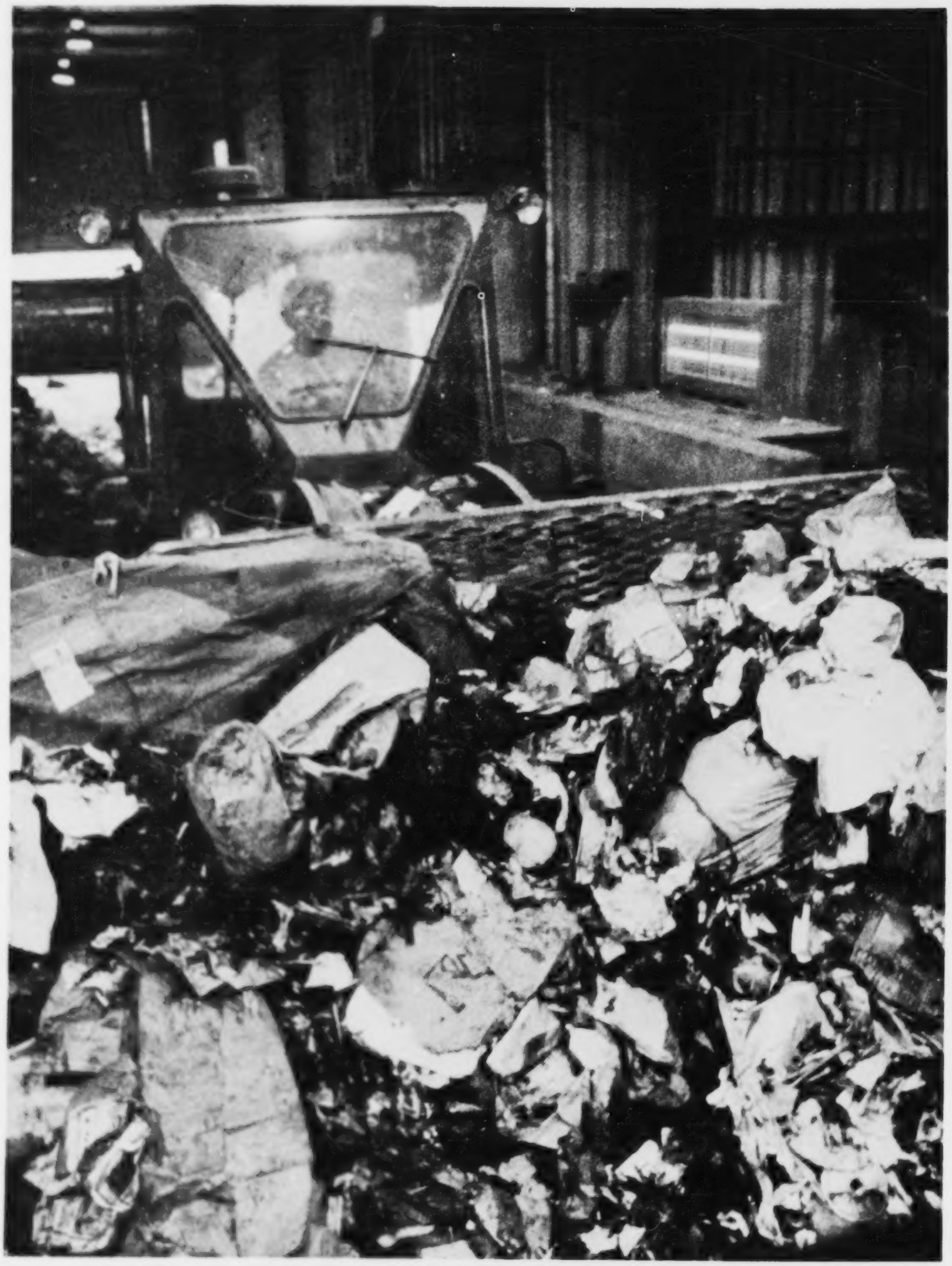

Figure 6. Front loader on refuse weigh scale.

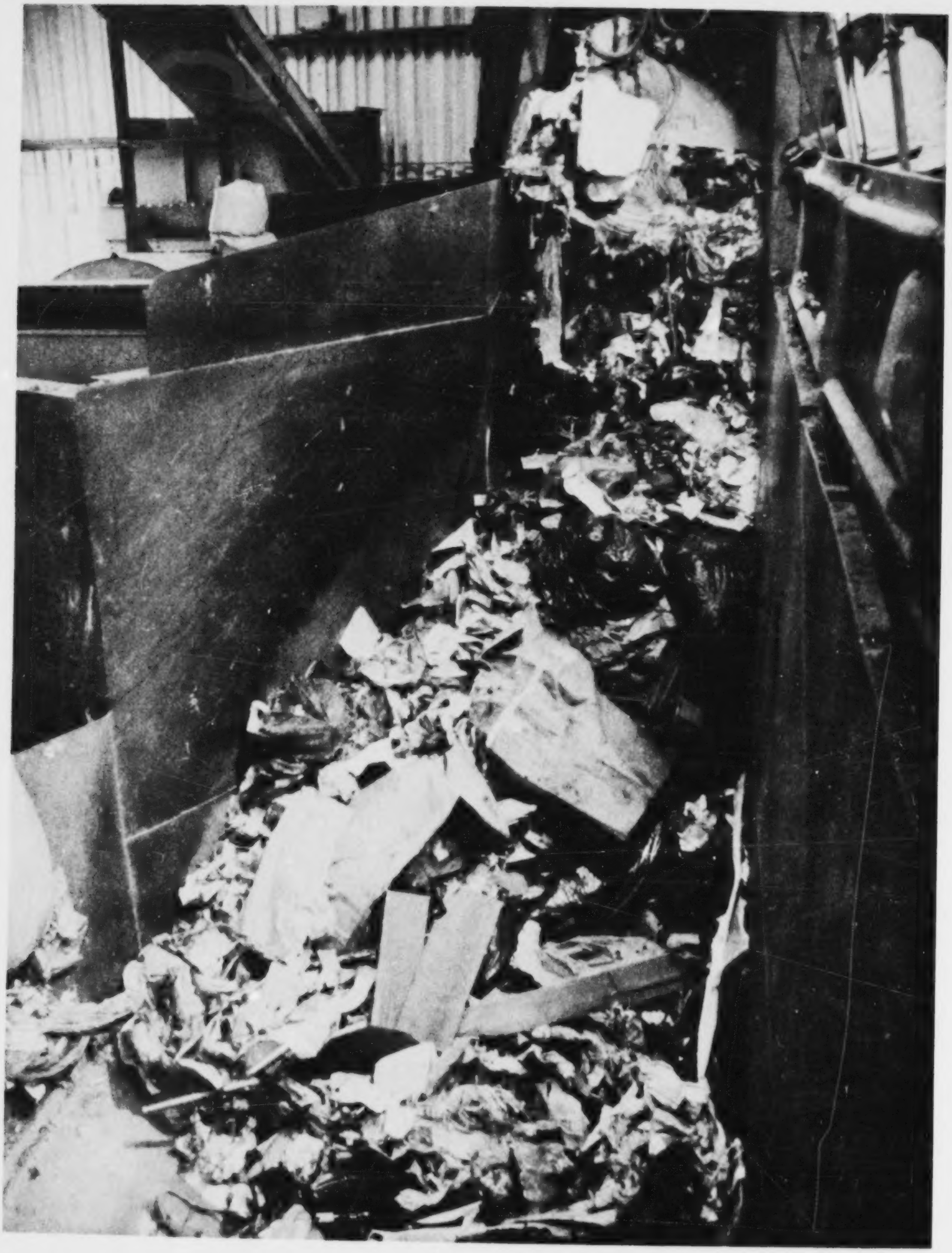

Figure 7. Refuse on apron conveyor to hammermill.

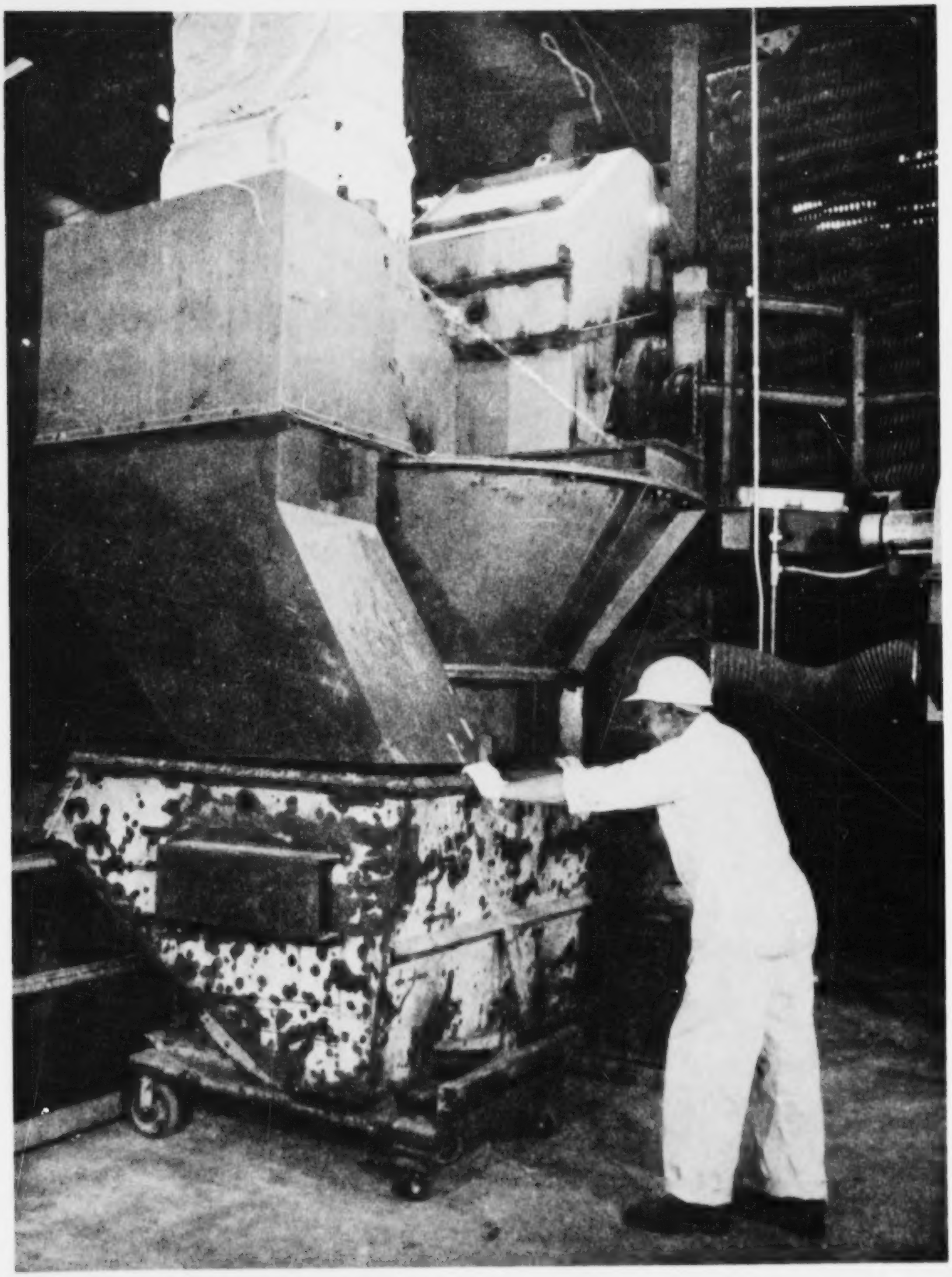

Figure 8. Vertical shaft hammermill.

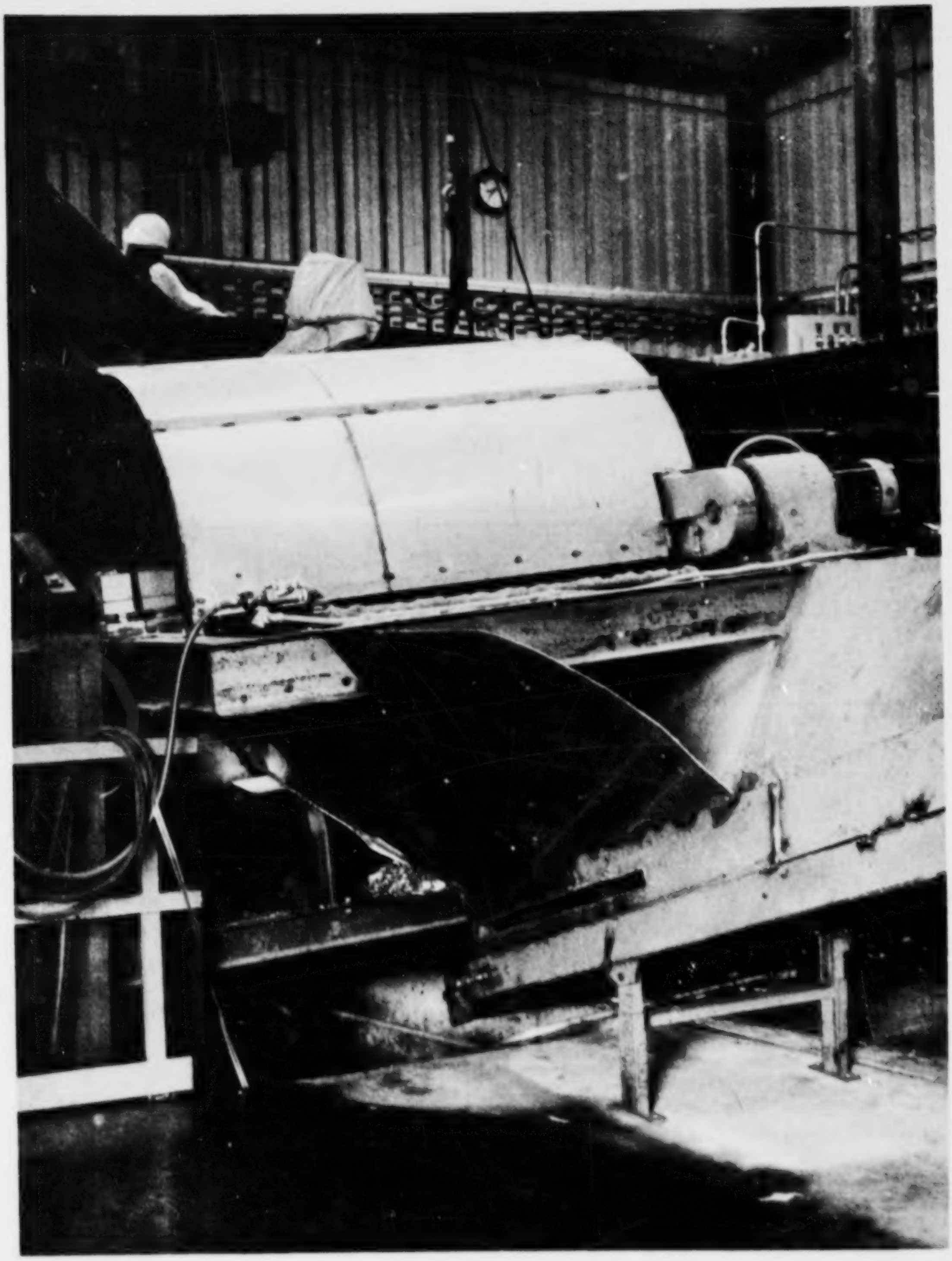

Figure 9. Drum magnetic separator.

TABLE 1. COMPONENT ANALYSIS OF REFUSE*

Wet Basis	Wt. %	Range (Wt. %)
Paper	38	25-60
Food	20	10-30
Yard	13	10-20
Wood	3	2-4
Plastic	1	0.5-2
Textile	1	0.5-4
Rubber & Leather	1	0.5-3
Glass	11	5-25
Ferrous Metal	7	5-9
Non-Ferrous Metal	1	0.2-1
Dirt & Ash	4	1-6
	100%	

Moisture included in above 26%

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*(1) C. T. Moses, J. R. Rivero; "Design and Operation of the PUROX System Demonstration Plant, "Fifth National Congress on Waste Management Technology and Resource Recovery, Dallas, Texas, 1976.

TABLE 2. ULTIMATE ANALYSIS OF REFUSE*

Component	Weight %
H_2O	26.0
C	25.9
H	3.6
O	19.9
N	0.47
S	0.10
Cl	0.13
Metal	8.0
Glass	11.0
Ash	4.0
	100.0

Higher Heating Value 11.61 MJ/kg (4,992 Btu/lb) moisture is driven from the refuse. As refuse descends down the shaft, it contacts high temperature gas and the organic material in the refuse begins to pyrolyze. In the pyrolysis reactions, cellulosic material is broken down into smaller molecules which volatilize into the hot gas stream. Coincidentally, hot gas produced by combustion of char in the hearth undergoes water-gas shift and carbonization reactions with the refuse. The complex mixture of gas and refuse undergoes a variety of reactions which result in the final offgas composition. Gas typically leaves the converter between 93 and 316 degrees C (200 and 600 degrees F) with a wet bulb temperature between 77 and 82 degrees C (170 and 180 degrees F).

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*(1) C. T. Moses, J. R. Rivero; "Design and Operation of the PUROX System Demonstration Plant, "Fifth National Congress on Waste Management Technology and Resource Recovery, Dallas, Texas, 1976.

Oxygen blown into the hearth reacts with the char residue from pyrolysis. The hearth operates at a temperature of about 1,650 degrees C (3,000 degrees F) in order to slag the inorganic portion of the refuse. Molton slag pours from the hearth into a water quench tank. Cooled slag is removed from the bottom of the tank by a drag conveyor and deposited in a dumpster for removal (Figure 10). A typical slag composition from refuse operation is shown in Table 3. It is similar to the composition of soda-lime or bottle glass which is its main constituent. Most of the inorganic residue from the refuse is bound in the glassy slag.

TABLE 3. ANALYSIS OF TYPICAL PUROX SYSTEM RESIDUE

	Weight %, Expressed as Oxide	
		Range
Silicon	59.7	57-62
Aluminum	10.5	9-13
Calcium	10.3	9-12
Sodium	8.0	7-10
Iron	6.2	1-8
Magnesium	2.2	1-4
Potassium	1.0	-
Other	2.1	-

Fuel gas is used in heating torches at the slag tap to maintain slag fluidity at the pouring point from the converter. It is also used in the tuyeres to preheat the oxygen at the injection point to preclude local chilling by cold oxygen. The energy required to preheat the oxygen to the hearth temperature of 1,650 degrees C (3,000 degrees F) from 15 degrees C (60 degrees F) is 988kJ/kg (425 Btu/lb) of oxygen. This is equivalent to 0.009 kg (0.02 lb) of natural gas or 0.036 kg (0.08 lb) of product gas per kg of oxygen. In a commercial plant, product gas would be recycled to provide this energy. Although the net

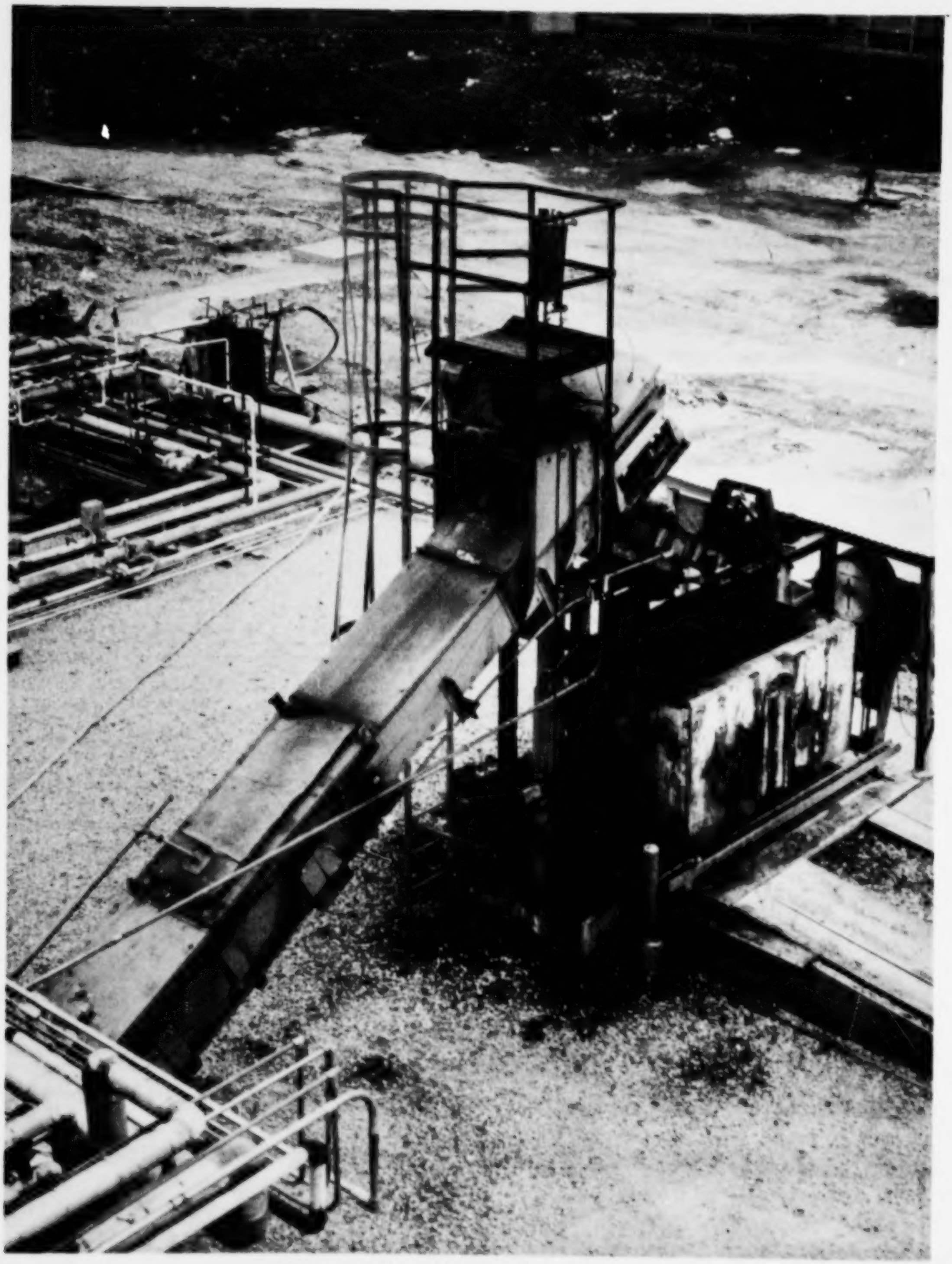

Figure 10. Slag Conveyor

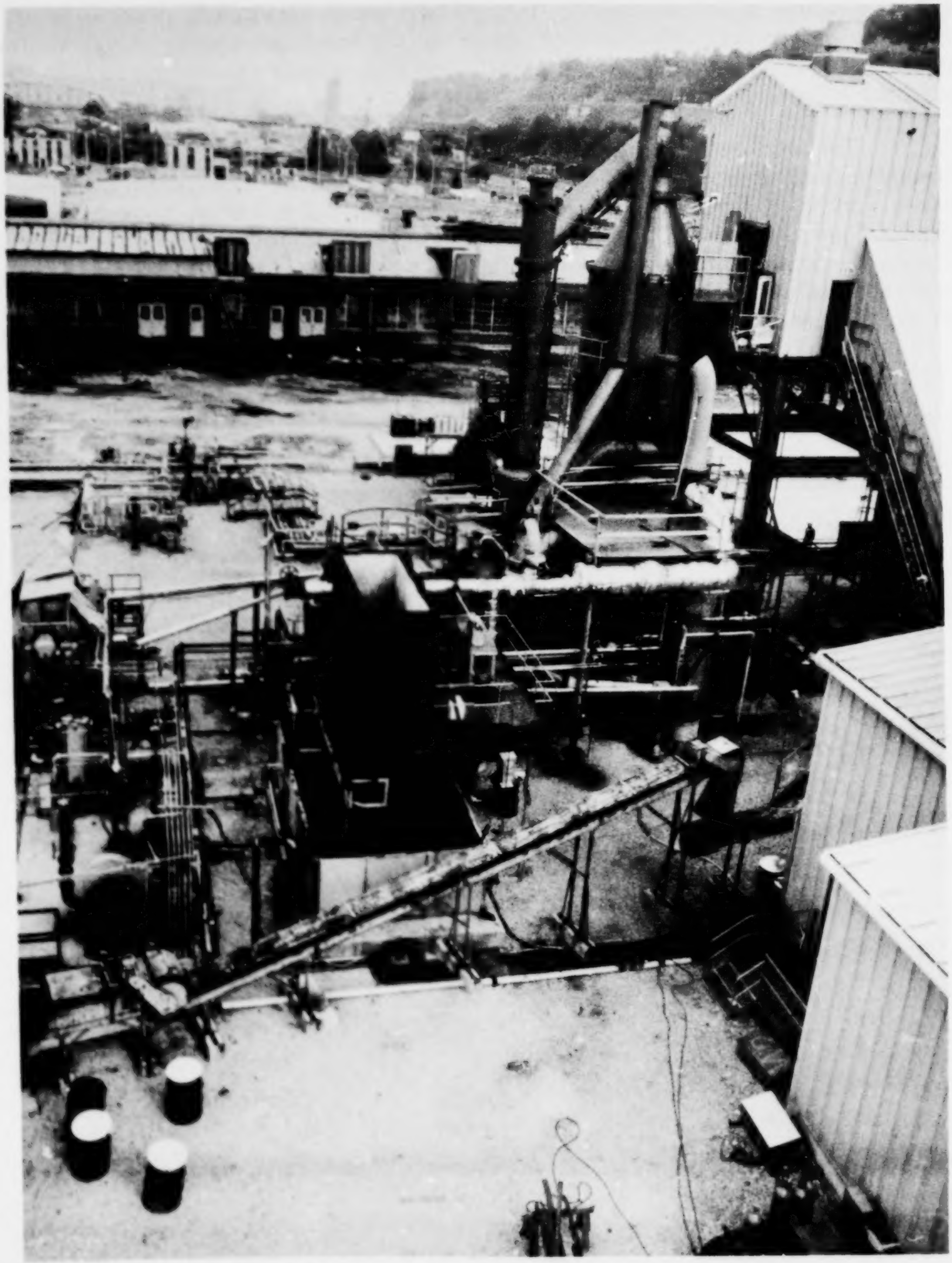

Figure 11. Converter and gas cleaning system.

quantity of gas produced per Mg (ton) of feed might be slightly reduced with recycle, the overall efficiency of conversion of the input energy to gas would remain above 70 percent since a significant part of this recycle energy is utilized in gasifying feed material.

The organic fraction of the refuse after conversion to a gas, exits the converter and is processed in the gas cleaning system. The gas is cleaned by water scrubbing followed by electrostatic precipitation. After cleaning, the product gas is cooled in a condenser to remove moisture prior to use of the gas. The converter, gas cleaning train, and combustor are shown in Figure 11. A typical product gas analysis is shown in Table 4. In the demonstration plant at South Charleston, West Virginia, the gas is flared.

TABLE 4. ANALYSIS OF TYPICAL PUROX SYSTEM PRODUCT GAS

Volume % - Dry Basis	Typical	Range
H_2	23	21-32
CO	38	29-42
CH_4	5.0	4-7
C_2H_2	0.7	0.2-1.5
C_2H_4	2.1	1-3
C_2H_6	0.3	0.1-0.5
C_3	0.6	0.2-1.3
C_4	0.5	0.1-0.8
C_5	0.4	0.1-0.6
Higher Hydrocarbons	0.5	0.25-1.4
CO_2	27	20-34
N_2 + Ar	1.5	0-2.0
H_2S	0.05	0.02-0.06
CH_3OH	0.1	0.05-0.15
Organic Vapors *	0.2	0.1-0.4
Water Content at 38 degrees C (100 degrees F), volume % = 6		
Heating Value, Dry Basis, MJ/Nm^3 (Btu/S ft^3)		
Higher	14.6 (370)	11.8-15.4 (300-390)
Lower	13.6 (345)	11.0-14.2 (280-360)

*Higher alcohols, aldehydes, ketones, organic acids

The scrubber water-particulate slurry is separated from the gas stream and sent to a solid/liquid separation system. The system consists of a slurry tank, a vacuum filter, a filtrate tank, and pumps and piping. Filtrate from the system is recycled for reuse in the scrubber. The particulate is fed to the hearth for disposal.

Typically approximately 0.28 Mg (0.31 ton) of wastewater is produced during the conversion of 1.0 Mg (1.1 tons) of municipal refuse into product gas, slag, and wastewater. The properties of this wastewater as-produced, and after treatment in an oxygen activated sludge process are summarized in Table 5. Dilution by a factor of 20:1 with fresh water or municipal sewage is used during biological treatment.

TABLE 5. ANALYSIS OF TYPICAL PUROX SYSTEM WASTEWATER

	As-Produced	After Oxygen Activated Sludge Treatment*
BOD_5	52,000 ppm	195 ppm
COD	77,000 ppm	381 ppm
Soluble Carbon	22,000 ppm	99 ppm
pH	3.7	7

*Assumes wastewater is then discharged into municipal sewer.

The operating rate of the converter is changed by varying the rate of oxygen injection into the hearth. The hearth operates at a fuel-rich condition to minimize oxygen consumption and maximize fuel gas production. Therefore the rate at which refuse is dried, pyrolyzed, combusted, and slagged is set by the rate of oxygen which supplies the necessary energy for the drying, pyrolysis, and slagging steps. To maintain the fuel-rich hearth condition, refuse is fed into the converter periodically with the intent of maintaining as constant a bed heighth as possible since this provides maximum heat utilization and hence conversion efficiency. The slag in the hearth is maintained at a fluid condition by the high temperature combustion of fuel with oxygen. The fluid slag drains continuously from the tap into the quench tank. The basic control parameters are setting the oxygen flowrate for a desired refuse processing rate and operating the front end to maintain a full converter condition at the desired rate.

SECTION 5

PUROX SYSTEM FACILITY EQUIPMENT DESCRIPTION

The PUROX System demonstration plant in South Charleston, West Virginia, was built in 1974 to demonstrate oxygen pyrolysis of mixed municipal refuse. It has been modified since original construction. The plant is shown in its present configuration in Figure 12. The number following each piece of equipment refers to Figure 12.

The shredder (D) is a Heil (Tollemache) vertical shaft hammermill driven by a 149 kw (200 horsepower) electric motor. It has a rated capacity of 13.6 Mg (15 tons) per hour. Because the PUROX System operates continuously, the hammers must be resurfaced every few days and the interior wear surfaces must be built up periodically. As a result of these requirements, the demonstration plant shredder requires 2 or 3 hours of maintenance each day.

The shredder is equipped with an overload protection circuit which stops the shredder feed conveyor (E) when shredder motor current reaches a predetermined value. This allows the hammermill to continue grinding without increasing its load. When motor current drops below the set point, the shredder feed conveyor restarts. The shredder is also equipped with an interlocked starting circuit which prevents starting the shredder unless the magnetic separator, the shredder discharge conveyor (E), and the shredder motor cooling fan are operating. This prevents clogging of the shredder with discharging material and overheating of the shredder drive . The shredder is automatically stopped if any of these components malfunctions. The shredder is controlled by the feed system operator who feeds in response to the converter demands for refuse.

The magnetic separator (F) is an Eriez drum type magnetic separator. It is suspended 0.25 m (10 inches) above the shredder discharge conveyor and discharges to a belt conveyor (G) installed perpendicular to the shredder discharge conveyor. The magnet is contained in a 1.2 m (four foot) drum operating at 480 volts. The magnetic separator and metals discharge conveyor (G) are controlled by the feed operator.

The feeder feed conveyor (1) is an apron type conveyor which transports refuse from the shredder discharge conveyor to the refuse feeder. The refuse

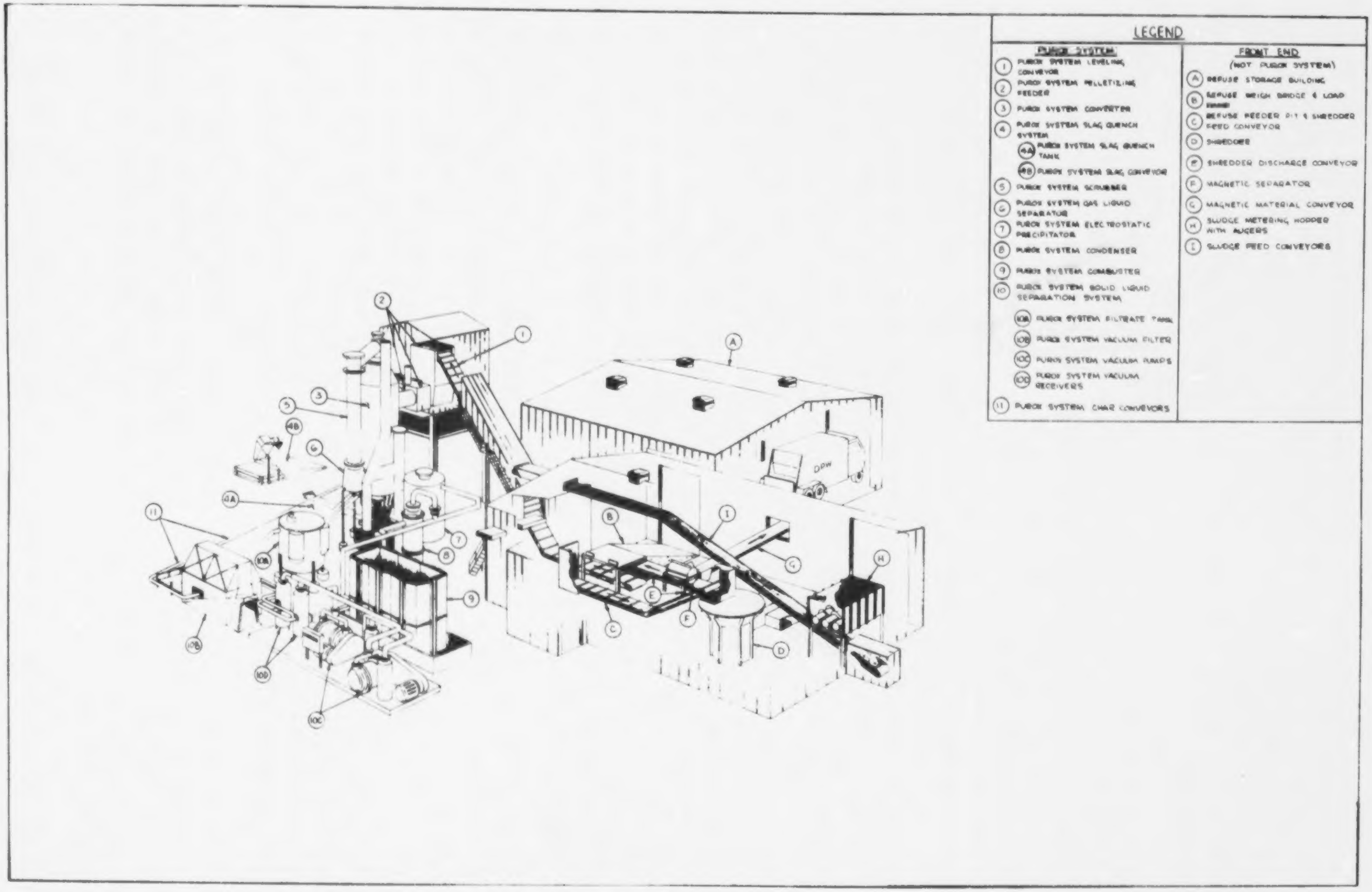
LEGEND
PUROX SYSTEM
1 PUROX SYSTEM LEVELING CONVEYOR
2 PUROX SYSTEM PELLETIZING FEEDER
3 PUROX SYSTEM CONVERTER
4 PUROX SYSTEM SLAG QUENCH SYSTEM
4A PUROX SYSTEM SLAG QUENCH TANK
4B PUROX SYSTEM SLAG CONVEYOR
5 PUROX SYSTEM SCRUBBER
6 PUROX SYSTEM GAS LIQUID SEPARATOR
7 PUROX SYSTEM ELECTROSTATIC PRECIPITATOR
8 PUROX SYSTEM CONDENSER
9 PUROX SYSTEM COMBUSTER
10 PUROX SYSTEM SOLID LIQUID SEPARATION SYSTEM
10A PUROX SYSTEM FILTRATE TANK
10B PUROX SYSTEM VACUUM FILTER
10C PUROX SYSTEM VACUUM PUMPS
10D PUROX SYSTEM VACUUM RECEIVERS
11 PUROX SYSTEM CHAR CONVEYORS
FRONT END
(NOT PUROX SYSTEM)
A REFUSE STORAGE BUILDING
B REFUSE WEIGH BRIDGE & LOAD [illegible]
C REFUSE FEEDER PIT & SHREDDER FEED CONVEYOR
D SHREDDER
E SHREDDER DISCHARGE CONVEYOR
F MAGNETIC SEPARATOR
G MAGNETIC MATERIAL CONVEYOR
H SLUDGE METERING HOPPER WITH AUGERS
I SLUDGE FEED CONVEYORS
1
2
3
4A
4B
5
6
7
8
9
10B
10C
10D
11
A
B
C
D
E
F
G
H
DPW

Figure 12. PUROX system facility for sludge/refuse codisposal, South Charleston, West Virginia.

leveler is a belt conveyor installed above the feeder feed conveyor. The height of the leveler above the feed conveyor can be adjusted between 0.03 and 0.25 m (1 and 10 inches). The leveler maintains an even burden on the refuse feeder by keeping the level of refuse on the feeder feed conveyor constant. The leveler is controlled by the feed system operator, and starts whenever the feeder feed conveyor is started.

The refuse feeder (2) has been designed by Union Carbide Corporation to perform three functions. It compacts shredded refuse into a pellet, introduces the pellet into the converter, and provides a gas seal for the converter.

The feeder contains nine principal parts; the refuse hopper, vane, two cylinders, two rams, two restrictors and the hydraulic power package. The refuse hopper receives refuse from the feeder feed conveyor. Attached to the refuse hopper is a Drexelbrook capacitance type level detector which actuates a feeder overload prevention system. When the level in the refuse hopper becomes too high, the feeder feed conveyor is stopped. This prevents refuse from overflowing to the surrounding area. The vane directs incoming refuse to one of two cylinders. The rams force the refuse in their cylinder through a restrictor and into the converter. The restrictors open and close to maintain the hydraulic pressure on the ram within a band which results in the formation of pellets which maintain their integrity in the converter. The hydraulic power unit consists of hydraulic pumps, valves and controls which automatically operate the feeder in the correct sequence. The gas seal is formed by pellets in the feeder which have not entered the converter and by a nitrogen purge through the cylinders. The feeder can be operated remotely by the feed system operator or locally at the feeder.

The refuse converter (3) is a vertical shaft furnace approximately 3 m (10 feet) in diameter and 13.4 m (44 feet) high. The upper section of the converter is a cylindrical carbon steel shell lined with 0.10 m (4 inches) of refractory. Pyrolysis gas exits from the top into the gas scrubber. The converter is equipped with 9 nuclear sensing devices which detect the presence of refuse at different levels. Ports for insertion of a poker to verify the refuse level are also installed. The nuclear detector at the 3.7 m (12 foot) level actuates a low bed level alarm when no refuse is detected. A thermocouple is installed at the top of the converter to measure the offgas temperature.

The lower section, or hearth, is a refractory lined cone. Fuel gas and oxygen for combustion of carbonaceous material are introduced by water-cooled nozzles called tuyeres. Slag forms a pool on the hearth floor and is continuously tapped through an opening in the hearth wall. Cooling water is supplied to hearth components and to the hearth walls.

The quench tank (4A) is a water filled tank installed to provide a 1.9 m (76 inches) deep water seal below the slag tap. It has two functions, cooling the molten slag and providing a pressure seal for the converter. A recirculation system replaces water in the slag duct with water from the main volume of the tank to suppress steam formation and also to control tank level. The tank is also provided with a temperature controller to maintain correct tank temperature. Slag is removed from the quench tank by a drag conveyor. A low pressure alarm is installed on the recirculation pump discharge.

The slag conveyor (4B) is a drag type conveyor manufactured by Taunton Engineering. It is equipped with a heavy duty chain and is driven by a 2.2 kw (3 horsepower) electric motor. The conveyor operates at a speed of 6.7 m (22 feet) per minute. It is equipped with a protective trip which stops the conveyor and sounds an alarm if motor current exceeds a predetermined level. The trip protects the conveyor should it become jammed by slag. The conveyor is reversible to facilitate clearing jams.

The product gas scrubber (5) is a water spray scrubber consisting of spray nozzles installed in the product gas discharge line. The nozzles are designed to permit removal of an individual nozzle during operation. The nominal scrubber water flow is 6.31×10^{-3} m^3/sec (100 gallons per minute).

The purpose of the product gas scrubber is two-fold. It removes 90-95 percent of the particulate from the product gas. It also cools the product gas from its exit conditions to near its wet bulb temperature.

The offgas line terminates in a gas-liquid separator (6) 1.83 m (6 feet) high and 1.4 m (54 inches) in diameter. Liquid is withdrawn from the bottom through two 0.25 m (10 inch) lines. Gas exits horizontally into a 0.61 m (24 inch) line and goes to the electrostatic precipitator inlet.

The electrostatic precipitator (ESP) (7) is a Research Cottrell tube type precipitator. It is a standard unit containing 60 tubes which provide approximately 10.5 square meters (1,131 square feet) of collection area. Nominal gas flow rate is 2.95 cubic meters per second (6,250 cubic feet per minute) at design conditions.

The ESP is used to remove any fine particulate that was not removed during the scrubbing process and to collect the fine oil mist that is produced as the gas is cooled to its wet bulb temperature.

The ESP is supplied with 450 volt alternating current (AC) which is stepped up and rectified to supply direct current to the precipitator discharge electrodes. An automatic control system adjusts the AC input to maintain optimum precipitation conditions. The control system is also equipped with a low voltage alarm and an overload protection circuit. The low voltage alarm actuates if primary voltage is below 130 volt AC for a set period of time. The overload protection circuit protects the rectifier by de-energizing the high voltage transformer if a portion of the circuit is overloaded. The ESP shell is equipped with a capacitance type oil level sensor which actuates an ESP high level alarm. A nuclear level detector is also installed.

Six high pressure steam nozzles are installed in the ESP base directed at the pumpout trough. They are used to heat the accumulated tar and oil for pumping. A Moyno progressing cavity pump is used to remove the oil. Steam is also supplied to the ESP shell for heating. A nozzle installed on the top of the ESP is used to spray cleaning solvent onto the tubes.

The product gas condenser (8) is a vertically mounted shell and tube heat exchanger. It cools the gas to approximately 27 degrees C (80 degrees F) to condense wastewater following gas cleaning in the ESP. Product gas enters through a connection at the top of the condenser and exits from the side of the condenser. Condensate is withdrawn from the bottom of the condenser. Cooling water is applied to the shell side. The condenser is equipped with a capacitance type level sensor which actuates an alarm and operates a solenoid valve and pump through a timer. The condensate is normally returned to the scrubber water slurry tank.

The combustor (9) is a National Air Oil (NAO) natural draft combustion chamber. It is equipped with 12 NAO jet mix vortex burners supplied from a common 0.3 m (12 inch) header. The burners are supported in a tall chamber. The walls of the 3.4 m by 1.2 m by 6.1 m (11 foot by 4 foot by 20 foot) chamber are lined with 0.1 m (4 inches) of refractory, and are supported by legs at each corner. A pilot burner, supplied with 0.1 MPa (15 p.s.i.g.) natural gas, is located at each corner. The entire unit is surrounded by an acoustical fence. The combustor is designed for a nominal flow of 1.0 cubic meters per second (2,200 cubic feet per minute) at standard conditions of 15 degrees C (60 degrees F) and 0.1 MPa (one atmosphere) pressure.

The slurry and filtrate tanks (10A) are formed by a tank to which legs and a baffle dividing the tank into halves have been added. The capacity of each half is 9.5 cubic meters (2,500 gallons). A 2.2 kw (3 horsepower) "Lightnin" mixer is installed on the slurry side of the tank.

The vacuum filter (10B) is a rotary drum type vacuum filter supplied by Ametek Engineers. The drum is 1.5 m. (5 feet) in diameter and 2.1 m. (7 feet) long. Polypropylene monofilament filter cloth is used as the filter medium.

The vacuum pumps (10C) are Nash L-7 and CL-702 models and are operated in parallel. Filtrate is collected in two vacuum receivers (10D) 0.61 m (24 inches) in diameter and 1.5 m (60 inches) tall, and then pumped to the filtrate tank. One vacuum receiver was purchased from Ametek and the second was fabricated locally. The filtrate pump is a self-priming Durco pump rated at 0.011 cubic meters per second (180 gallons per minute) at a 15.2 m

(50 foot) head, and it is driven by a 3.7 kw (5 horsepower) motor. The slurry tank, vacuum filter, and vacuum receivers are equipped with level control systems. Level is sensed in the tanks by Drexelbrook level detectors.

The particulate conveyors (11) are 0.15 m (6 inch) diameter screw conveyors manufactured by Jeffrey Manufacturing. The screws have 0.15 m (6 inch) pitch and are driven by 3.7 kw (5 horsepower) motor. The total length is 20.7 m (68 feet). The feeder is a pneumatically operated ram feeder.

SECTION 6

EQUIPMENT MODIFICATIONS FOR CODISPOSAL OF SEWAGE SLUDGE AND REFUSE

Processing sludge filter cake required the installation of additional materials handling equipment at the facility. The new equipment is shown in Figure 12. The major additions are a dumping station, a small front loader, a metering hopper and a rubber belt conveyor.

Sludge cake is hauled to the site in dump trucks and is weighed at the plant truck scales prior to dumping. The sludge is then dumped on a concrete pad adjacent to the east wall of the shredder building (Figure 13). The pad is surrounded on three sides by a 1.5 m (5 foot) wall and has a roof. A small front loader is used to scoop up sludge cake for loading into the metering hopper (Figure 14). The metering hopper delivers a metered flow of sludge onto the sludge conveyor. Sludge is discharged from the sludge conveyor onto the feeder feed conveyor where it is added to shredded refuse. The combined refuse and sludge stream was fed using the refuse feeder.

The metering hopper (H) is manufactured by Taunton Engineering Company of Taunton, Massachusetts. It has vertical sidewalls and a flat bottom. Three 0.3 m (12 inch) diameter augers traverse the bottom (Figure 15). They are driven by a 2.2 kw (3 horsepower) motor with a variable speed drive. Sludge rate is varied by adjusting the auger speed. Sludge is discharged onto the sludge conveyor from a chute at one end of the hopper. The nominal capacity of the hopper is 5.7 cubic meters (200 cubic feet).

The sludge conveyor (I) is a troughing type belt conveyor supplied by Stone Conveyor, Inc. (Figure 16). It is 0.46 m (18 inches) wide and driven by a 2.2 kw (3 horsepower) motor. The conveyor is 29 m (95 feet) long and consists of a 20 degree inclined section of 16.8 m (55 feet) followed by a horizontal section of 12.2 m (40 feet) (Figure 17). A belt wiper is installed to ensure complete discharge of the sludge.

Operation of the feed system is controlled by an operator. During automatic operation, the system starts and stops in conjunction with the refuse feed system. The control system includes a circuit which stops operation of the sludge system if the feeder feed conveyor is empty.

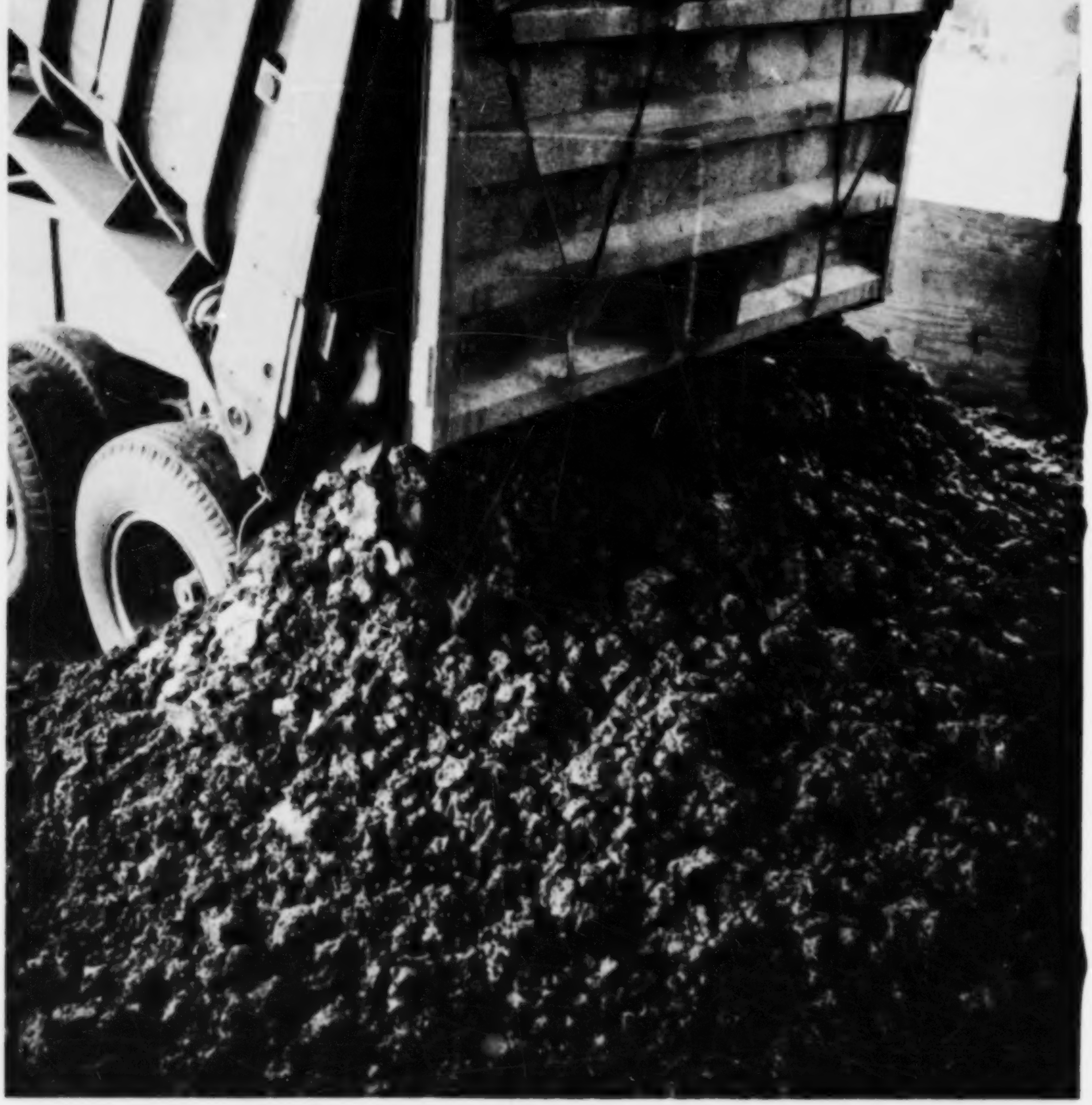

Figure 13. Sludge cake at dumping station.

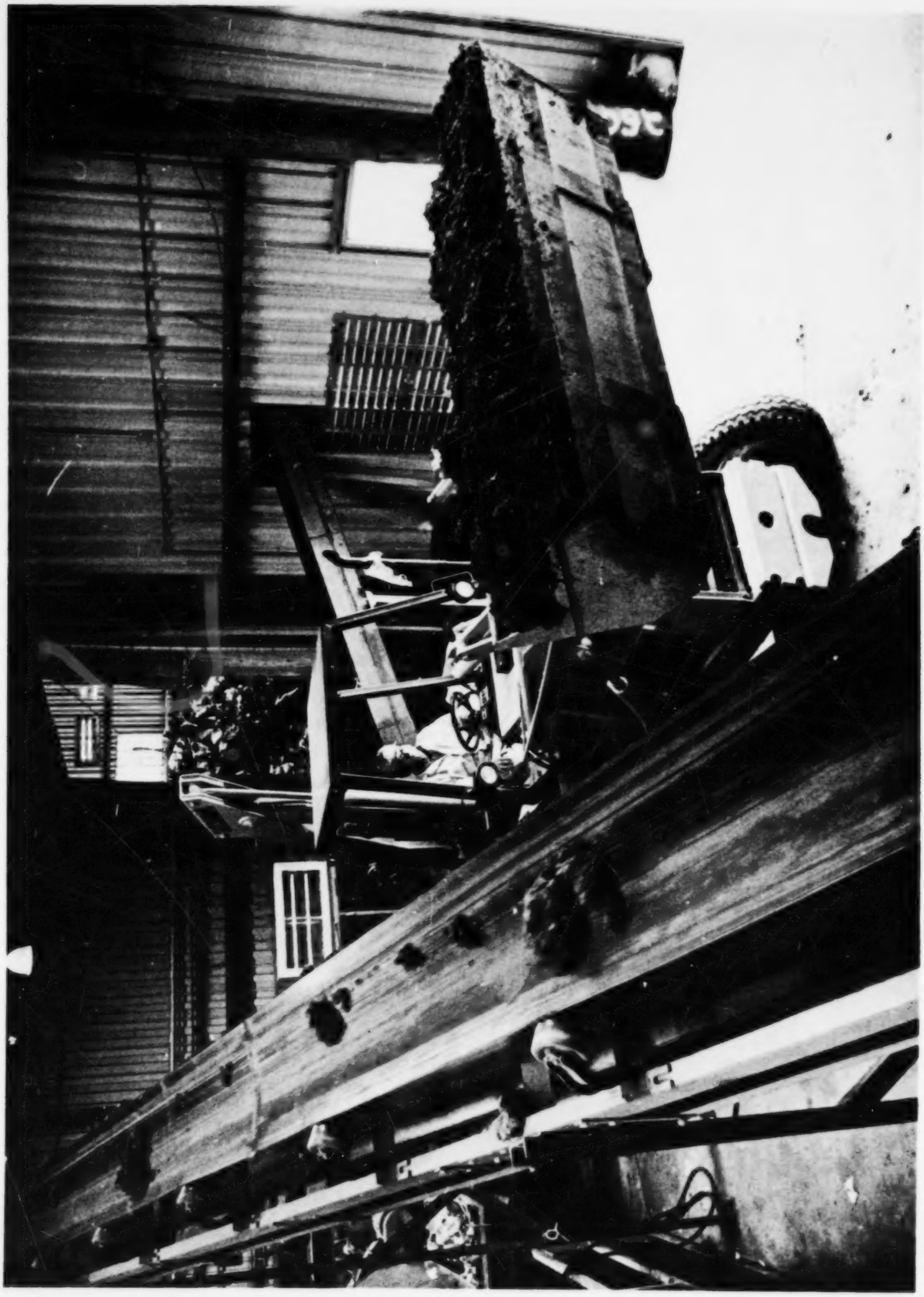

Figure 14. Front loader scooping sludge cake.

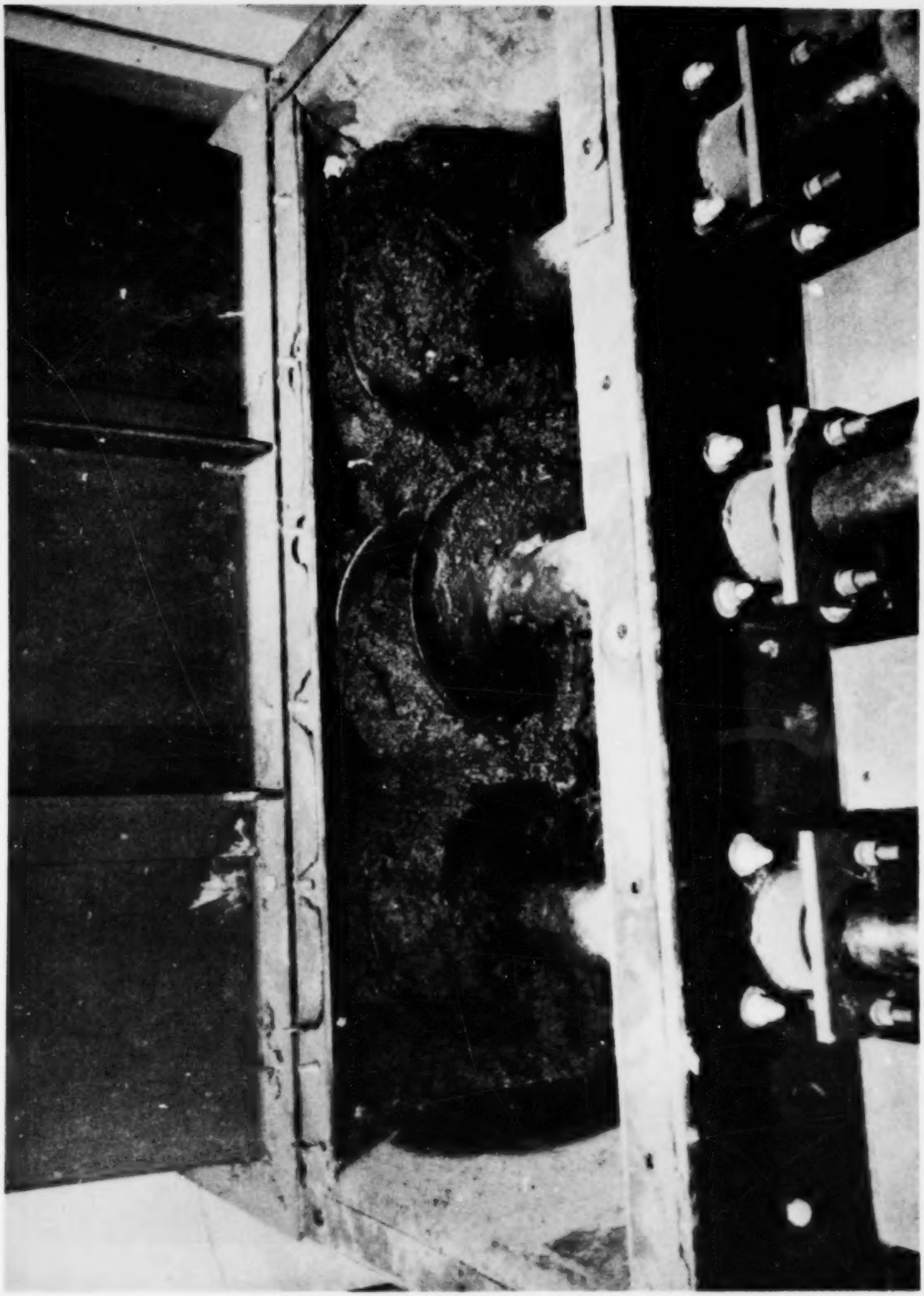

Figure 15. Metering hopper augers.

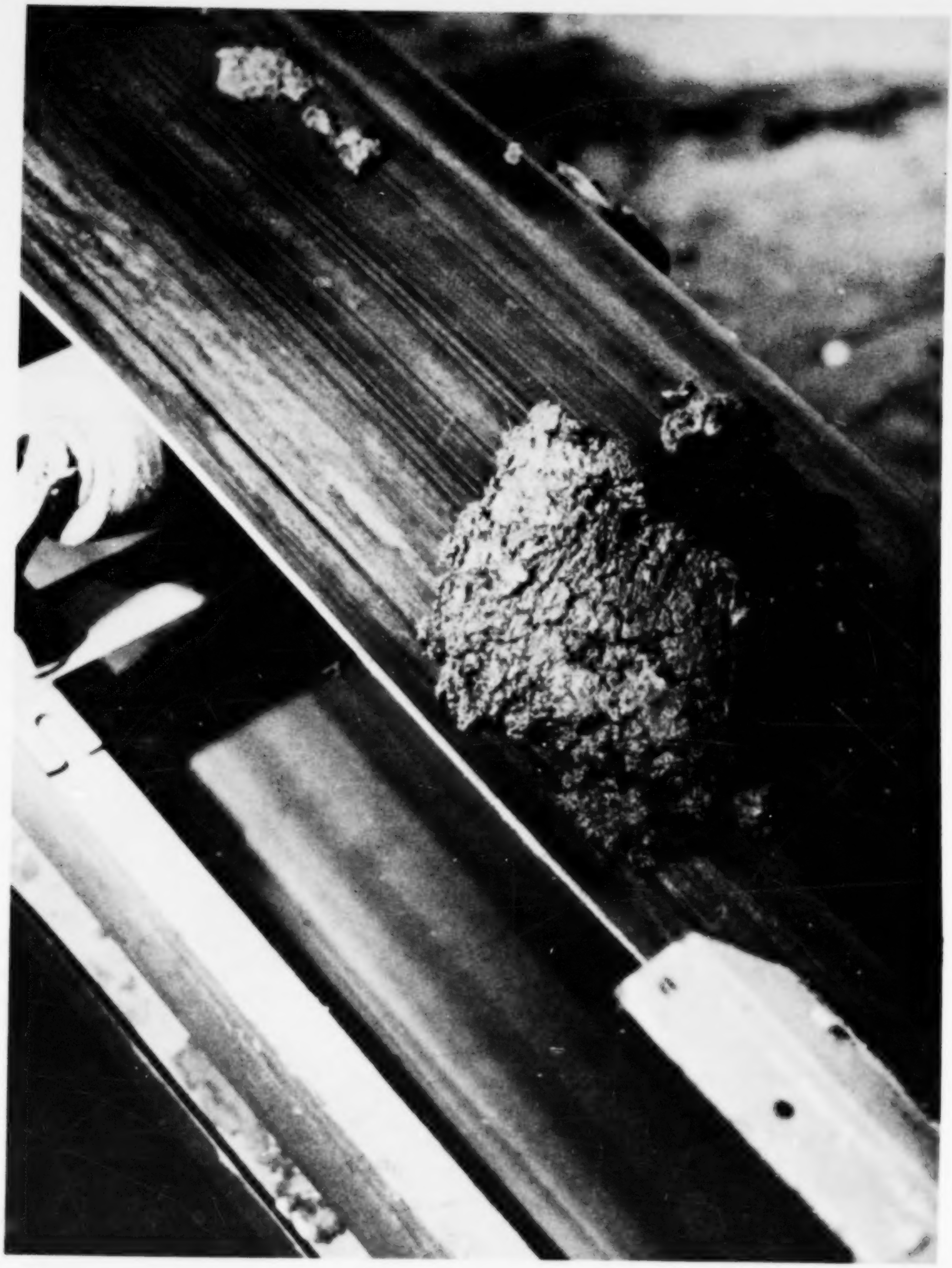

Figure 16. Sludge cake on troughing conveyor.

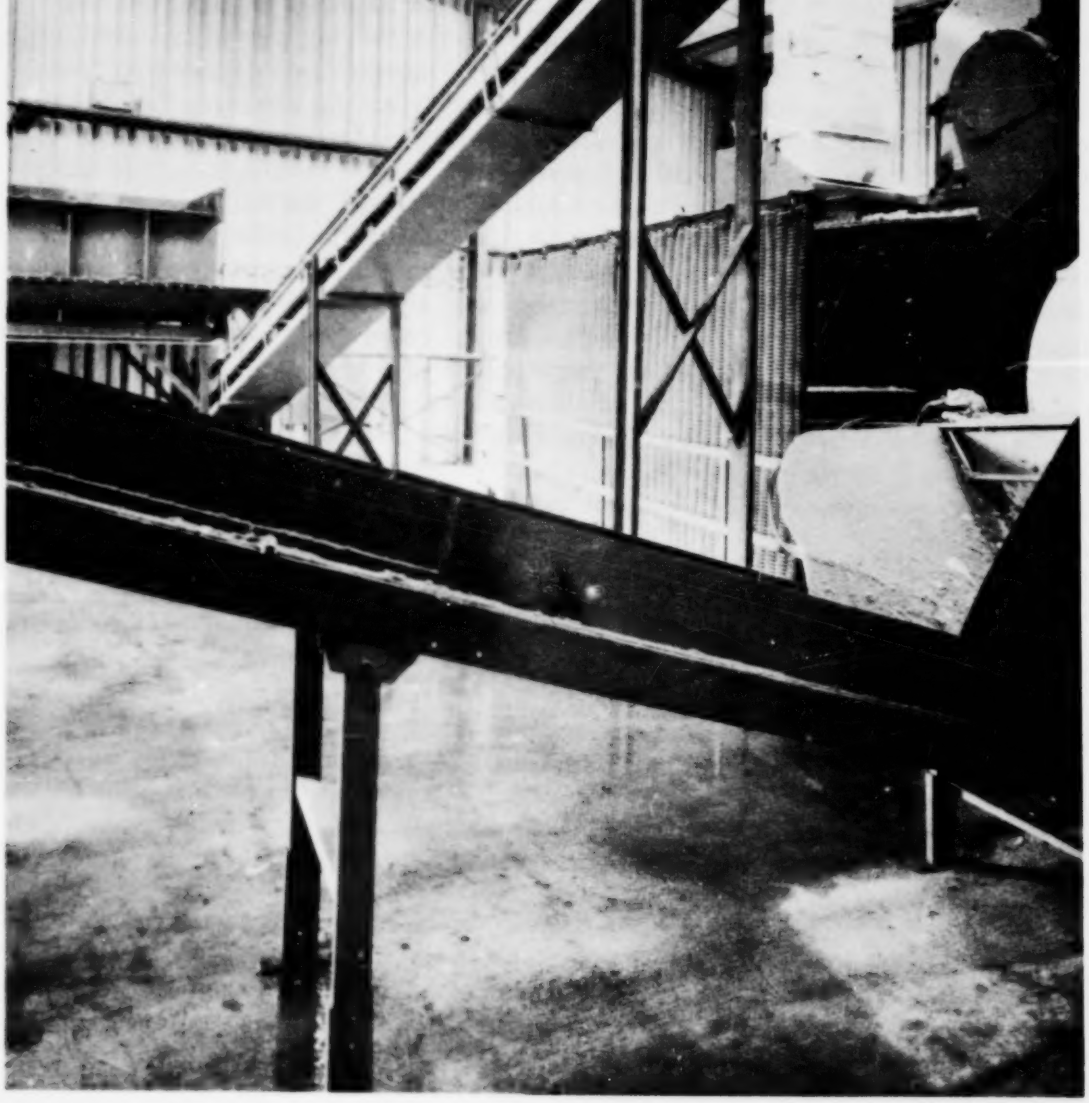

Figure 17. Metering hopper and troughing conveyor.

SECTION 7

SLUDGE-REFUSE CODISPOSAL TEST PLAN

The test program was planned to consist of a series of eight (8) test periods with a total duration of 64 days of 24 hour per day operation (see Table 6). Each test was to consist of four (4) days of codisposal followed by three days of refuse-only operation at reduced rate to flush the system of residues from the preceeding sludge test and to accumulate material for the following test. The intention was to begin the test series at low levels of sludge cake-to-refuse and to increase the ratio in successive tests. In addition, a test operating at the rated capacity of the unit was desired to determine performance at capacity. At the time the test plan was prepared, it was recognized that operation at capacity for an extended test would be difficult for two reasons: the available supply of refuse in the Charleston area would not permit operation above 136 Mg (150 tons) per day for more than one day without forcing a shutdown of the unit over the weekend when refuse was unavailable and the single-train design of the front end; i.e. the shredder and feeding system provided no redundancy to support sustained capacity operation. For these reasons, the operation was judged to be a high risk operation and hence scheduled as the last test.

The Charleston area was unable to supply sufficient quantities of sludge since much of the available supply was digested. However, an adequate supply of primary filter cake was located in Huntington, West Virginia, a distance of 60 miles from Charleston. This material was raw, primary sludge filter cake with a total solids content of 24 percent and a volatile solids content of about 45 percent. The volatile solids content was rather low in this sludge due to the mixing of industrial wastes from a metal alloying company with municipal waste. Sludge was available from Huntington on an as-needed basis.

Small quantities of raw primary filter cake were available from the South Charleston Waste Treatment Plant. This cake had a solids content of about 30 percent and was used in preliminary equipment tests and shakedown operation of the unit. Unfortunately, the material was not available in enough quantity to carry out a complete test phase.

TABLE 6. ORIGINAL SLUDGE CODISPOAL TEST PLAN*

Test No.	Sludge Source	Sludge Type	% Solids	Refuse Mg (ton)	Wet Sludge Mg (ton)	Total Mg (ton)	Wet Ratio Sludge/ Refuse	Dry Ratio Sludge/ Refuse
1	S.Chas.	Raw primary	30	91 (100)	6 (7)	97 (107)	0.07	0.02
2	Huntington	Raw primary	24	91 (100)	15 (17)	106 (117)	0.17	0.04
3	Pitts.	Primary & secondary	20	103 (114)	10 (11)	113 (125)	0.10	0.02
4	Pitts.	Primary & secondary	20	94 (104)	19 (21)	113 (125)	0.20	0.04
5	Pitts.	Primary & secondary	20	87 (96)	26 (29)	113 (125)	0.30	0.06
6	Pitts.	Primary & secondary	20	80 (89)	33 (36)	113 (125)	0.40	0.08
7	Pitts.	Primary & secondary	20	75 (83)	38 (42)	113 (125)	0.50	0.10
8	S.Chas.	Raw primary	30	181 (200)	12 (13)	193 (213)	0.07	0.02

*Codisposal operation conducted from 12 noon Monday until 12 noon Friday of each test week.

The test plan placed a heavy emphasis upon operation with secondary sludge. Unfortunately, the nearest substantial supply of secondary sludge cake was the Alleghany County Sanitary Authority Waste Treatment Plant in Pittsburgh, Pennsylvania, which produced a mixed sludge filter cake that was 60 percent raw primary and 40 percent secondary sludge. The hauling distance from Pittsburgh to Charleston complicated the logistics and increased the cost of mixed sludge testing.

The early operation with primary sludge went well in terms of both equipment and system performance. However, operation with mixed primary and secondary sludge did not proceed as well. The equipment used with these mixtures had not been mechanically verified prior to startup due to unavailability of the sludge. Equipment problems prevented processing of the high moisture mixed primary and secondary sludge over the full range of blends projected in the test plan.

In particular, the peculiar properties of high moisture content (75 percent) mixed sludge filter cake led to equipment and materials handling problems in the PUROX System feeding equipment. These handling problems were equipment specific related to the inadequate blending of sludge and refuse prior to pellet forming. With appropriate equipment selection and design, based upon the operating experience gained with this material, effective processing of high moisture sludge blended with refuse should be possible.

In light of the factors discussed above, the test program as executed differed from the original plan. The program as shown in Table 7 consisted of a set of seven test periods, six were with codisposal of sewage sludge and refuse and one was for collection of baseline, refuse only data. The codisposal tests included two with mixed sludge and four with raw primary sludge. The range of parameters studied included tests at wet sludge to refuse ratios from 0.06 - 0.23 corresponding to dry sludge to refuse ratios from 0.03 - 0.074; throughput rates from 59 to 106 Mg (65 to 117 tons) per day; and total moisture content of the refuse/sludge mixture up to 35 percent by weight.

In comparing the test program as executed with the original test plan, the ratios of sludge dry solids-to-refuse above 0.074 were not achieved. The use of mixed secondary sludge was limited to a sludge dry solids-to-refuse ratio of 0.049 due to the equipment problem stated previously. The capacity test was not conducted due to a desire to obtain as much operating data at high sludge ratios as possible and of course the limited refuse supply.

The impact of these modifications in the tests upon the basic goals of the test program is not serious. Operation was achieved at substantial sludge cake-to-refuse ratios. Detailed operating data was collected for the test periods. Useful operational experience was obtained in handling and processing sludge

TABLE 7. SLUDGE CODISPOSAL TEST SERIES

Test #	Source/Type	Sludge % Solids	Feed Rate Mg/d (ton/d)			Sludge/Refuse	
			Refuse	Sludge (Wet)	Total	Wet	Dry
1	H/RP	32.38	77.1 (85.0)	5.1 (5.6)	82.2 (90.6)	0.066	0.030
2	H/RP	27.47	75.3 (83.0)	7.4 (8.1)	82.7 (91.1)	0.098	0.036
3	P/MS	21.01	61.0 (67.3)	9.1 (10.0)	70.1 (77.3)	0.149	0.049
4	P/MS	20.25	78.0 (86.0)	10.5 (11.6)	88.5 (97.6)	0.135	0.035
5	-	-	73.5 (81.0)	-	73.5 (81.0)	-	-
6	H/RP	26.23	55.3 (61.0)	3.4 (3.7)	58.7 (64.7)	0.061	0.024
7	H/RP	22.32	86.2 (95.0)	20.1 (22.2)	106.3 (117.2)	0.234	0.074

H/RP - Raw primary sludge from Huntington, West Virginia

P/MS - Secondary sludge from Pittsburgh, Pennsylvania mixed with primary sludge in approximate ratio of 60% raw primary, 40% secondary cake through the PUROX System. Equipment limitations were identified and design changes and concepts have been identified which should provide improved performance for the codisposal process. A modified process (which will be discussed in more detail in Section 13) has been proposed in large part as a result of the operating experience gained during this program.

Equipment malfunctions with the previously untested particulate recycle system prevented recycle of particulate material throughout the test period. However, enough once-through scrubber water was sampled and analyzed to determine its composition and to determine its treatability. These analyses were used in computing the material balances.

The material and heat balances presented later are computed from direct measurement of quantities whenever possible. Projected results for system operation under standard operating conditions are also included. The disposition of trace metals under steady-state conditions with particulate recycle has been projected as follows. The results of trace metal balances indicate that the bulk of the metals exit in the slag. (See Section 12 for details). The scrubbing system is effective in removing the metals from the gas, and metals which do not return to the system in the particulate recycle loop will enter the wastewater stream where they would be concentrated in a waste sludge which could return to the PUROX System for eventual disposal in the slag or be disposed of by an alternate technique. Subsequent tests with refuse-only confirmed these projections.

The balances report particulate material as a product although it is normally recycled as a liquid (oil) and a solid (char) to the converter. In the material balances where the results projected for particulate recycle are presented, these streams have been converted into offgas and slag based on a model of the gasification and slagging process in the hearth of the converter which is discussed in Section 11. The following sections present a detailed discussion of the data collection and analysis, and of each test period.

SECTION 8

DATA COLLECTION AND SAMPLE ANALYSIS

Process rate data was obtained for the major process streams during each test period. Operating personnel measured the refuse, sludge, oxygen, fuel gas, metal, and slag rates as part of their normal operating procedures. The rate of the product gas stream was calculated from gas analysis results using helium as a tracer gas.

Each bucket of refuse entering the system was weighed by the front loader operator prior to dumping. The net weight of each load was recorded on daily tally sheets which were the source of refuse rate data. For each sample period, the cumulative weight of refuse processed was plotted as a function of time. A best fit straight line was drawn, and the slope of the line was computed. The slope was equal to the refuse rate of feed. This method of handling the data was used because refuse was fed intermittently in response to converter requirements and rates based on daily totals were erroneous. In addition, no method existed for measuring the converter refuse inventory. These two operating characteristics caused substantial errors when daily totals were used. Use of the graphical method minimized the chance of error, and also minimize the effect of feed system stoppages.

Each sludge load was weighed before it was added to the sludge hopper. The net weight of each load was recorded on tally sheets and totaled for each day. The same technique used to determine the refuse rate was used to obtain the sludge rate during each period.

Oxygen supplied to the converter was measured by several methods. An orifice plate provided a total flow signal to an oxygen flow integrator. Rotameters also provided flow indication for the hearth components supplied with oxygen. When oxygen flowrate was changed, the flows were calculated and recorded using both methods of indication. Oxygen consumed as a function of time was determined by reviewing all available oxygen flow measurements and using the best available data in the following order of preference: (1) oxygen totalizer, (2) total flow rotameter integrated over time, (3) individual component rotameters integrated over time and summed. The resulting data was plotted using the method used to determine refuse and sludge rate. The oxygen rate was equal to the slope of the best straight line.

Rotameters measured the flow of fuel gas to the hearth and the flow was integrated to determine quantity of fuel gas used. The plot of gas used versus time resulted in the fuel gas rate.

Slag fell from the slag conveyor into the slag dumpster which rested on a scale. The weight of slag in the dumpster was recorded prior to dumping. Slag production rate was determined from this data by applying the same method used for other streams. The weight of slag produced was plotted versus time and a straight line drawn to fit the data. The slope of the line was equal to the slag production rate.

Ferrous metal removed from the shredded refuse was conveyed to a dumpster for recovered metal. The dumpsters were weighed and the weight of metal was recorded. The ferrous metal recovery rate was determined using the same plotting method used for refuse, sludge, and slag.

Product gas flow rate per unit of feed was determined by using helium tracer gas. When gas samples were taken for component analysis a metered helium flow was injected into the hearth. The gas flow rate was calculated from the helium concentration in the product gas. Raw sample results were converted to a dry, nitrogen-free basis before calculating the gas flow rate. These corrections were made due to nitrogen purges of converter components near the gas sample port which caused a high concentration of nitrogen in the samples. Samples with helium concentration less than one volume percent were not used for flow calculations. The gas production in cubic meters at 15 degrees C (cubic feet at 60 degrees F) and one atmosphere per Mg (ton) of material fed was determined for each gas sample using the following method. The gas production rate from the helium trace was divided by the total feed rate at the time of sampling (generally determined from the measured oxygen rate and the oxygen consumption ratio - oxygen/feed for that period).

Additional gas flow rate data was obtained from pitot tube measurements of gas velocity taken in conjunction with gas particulate samples. These measurements were taken downstream of the product gas condenser with a S-type pitot tube. Static and velocity heads were recorded every ten minutes during a two hour sample period, and probe location was changed every ten minutes to traverse the gas pipeline. Assuming plug flow and correcting for natural gas added to purge the ESP insulator compartments the volumetric flow rate was calculated from velocity measurements. Gas velocities typically varied 15 to 20 percent over any ten minute period. Average gas flow rates were calculated and gas production rates in cubic meters at 15 degrees C (cubic feet at 60 degree F) and one atmosphere per Mg (ton) of feed were determined using the same procedure described with the helium trace data.

Pitot tube measurements do include water and nitrogen from converter purges neither of which are reflected in the helium trace measurements. No gas analysis was available with the pitot tube data to correct for nitrogen and water.

The product gas was sampled for particulate material downstream of the gas condenser. One particulate sample was taken during each test period using EPA method 5, "Determination of Particulate Emissions from Stationary Sources"*. A Research Appliance Company "Stacksamplr" was used for sampling. The sample was analyzed immediately after completing the sampling process.

Char production was measured during two periods of recycle operation of scrubber water in the gas cleaning system. Measurements were taken at four different converter rates with refuse only between sludge codisposal tests. Char was collected in drums and the time to fill the drums was recorded. The drums were weighed and the weight of char recorded. Char moisture content was determined analytically. Using this data, the production rate of dry char in kilograms (pounds) per hour was determined. A least-square curve-fit of the char production data as a function converter rate resulted in a linear equation predicting char rate. The equation predicted no char production at an operating rate of 51.7 Mg/d (57 tons per day (TPD)) which was consistent with previous South Charleston experience. This equation was used to estimate the average char production during each test period.

Wastewater flowrate was calculated by difference between the entering streams and the established exit streams. Due to mechanical problems, operation of the gas cleaning system in a closed cycle was impossible during most of the test. Scrubber operation with once-through water resulted in several effluent streams and the net wastewater production was not measureable.

Samples of the major streams were taken during each test period. Sampling was performed by a data collection team. Analysis of the samples was performed offsite by several laboratories. The analytical techniques used are described in Appendix A.

Refuse samples were obtained during three test periods. Grab samples were taken in buckets at the end of the shredder discharge conveyor, and represented the shredded, magnetically separated refuse fed to the converter. Between 2 and 5 samples were taken during each test period and after completion of data collection, the samples were composited and reduced to a single 0.02 cubic meter (5 gallon) sample. The composite sample was delivered to Standard Laboratories, Inc. of Charleston, West Virginia for analysis.

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*(2) Federal Register, Vol. 36, No. 247, December 23, 1971.

Analyses of the refuse for moisture, ultimate analysis, heating value and trace elements were made.

A 0.004 cubic meter (one gallon) sample of sludge was taken from each truckload of sludge delivered. The sludge samples taken during each test period were composited and reduced to a 0.004 cubic meter (one gallon) sample. The sludge samples were also delivered to Standard Laboratories for analysis. Analtyical results include percent solids, percent volatile solids, ultimate analysis, heating value and trace elements.

Product gas samples taken from the top of the converter were obtained twice daily. A typical gas sample consisted of three gas sample tubes filled sequentially. Samples were obtained using a probe inserted into the converter. The gas passed through a glass wool filter to remove particulates prior to entering the sample tubes. A metered helium flow was injected into the converter hearth to act as a tracer gas for calculation of the gas flow rate.

Gas samples were taken using the following procedure. Sample tubes were purged with product gas for three minutes. After purging, the helium flow was set and run for three minutes to reach steady state. Three consecutive gas samples were then taken. Each sample tube was purged with product gas for two minutes prior to isolating the sample. After completion of sampling, the helium flow was stopped, the probe removed, and the gas samples were taken immediately to the laboratory for analysis. The samples were representative of the product gas downstream of the condenser since particulate was removed by the glass wool filter and water was condensed in the sample tubes. Gas samples were analyzed by Union Carbide Corporation, South Charleston Laboratories by emission mass spectroscopy.

Slag samples were taken in 0.004 cubic meter (one gallon) cans placed under the slag conveyor discharge. Up to 4 samples were taken on the final day of each sampling period. After completion of sampling, a composite slag sample was made. One quart of the slag composite was withdrawn and shipped to Union Carbide Corporation, Tarrytown Laboratories. The remaining slag was retained for leachate testing. Analysis of the slag was performed using a variety of methods including chemical, atomic absorption, x-ray fluorescence and induction coupled plasma techniques. Analyses were made for carbon, major constituents, and trace metals.

Wastewater samples were taken from the slurry tank. Due to mechanical problems, the gas cleaning system was operated on once-through scrubber water during the tests. Because of this mode of operation, the water samples were very dilute in trace metals and the resultant concentrations are often below detection limits. During subsequent periods of refuse only operation with particulate recycle, samples of filtrate were taken which were more representative of the wastewater.

Two wastewater samples were obtained during each day of the sample period. The samples were composited and the composite was delivered to Union Carbide Corporation, South Charleston Laboratories for analysis. Analyses were performed to determine grease and oil, chemical oxygen demand, biological oxygen demand, total organic carbon, suspended solids, and trace elements.

One set of samples were taken of both the oxygen and the fuel gas supplied to the converter. Samples were taken from the tuyere supply lines for each stream. They were analyzed by Union Carbide Corporation, South Charleston Laboratories using emission mass spectroscopy.

The particulate collected from the product gas during three test periods was shipped to Union Carbide Corporation, Tarrytown Laboratories for analysis. The induction coupled plasma spectroscopy was used to analyze the particulate for metals content.

Samples of slag leachate were obtained by the data collection team and were delivered to Union Carbide Corporation, South Charleston and Tarrytown Laboratories for analysis. The samples were prepared by placing 375 grams of composited, as-sampled slag in a beaker with 1.5×10^{-3} cubic meters of distilled water. The beaker was gently agitated by air bubbles for at least 48 hours. The leachate and a distilled water blank were sent to Union Carbide Corporation, South Charleston Laboratories for analysis. Analysis was for biological oxygen demand, (BOD_5), chemical oxygen demand, (COD), total organic carbon, (TOC), pH, chloride ion, and trace metals. Several leachate samples were also sent to Union Carbide Corporation, Tarrytown Laboratories for trace metal analysis.

SECTION 9

SUMMARY OF TEST PERIOD RESULTS

In this section summaries and comparisons for the various test periods are presented. Details of the calculation techniques and individual component results are collected in Appendices B - H. Some introductory comments on the calculation approach are also provided for background.

The unreliable operation of the particulate recycle system made measurement of wastewater production impossible during the test periods. This required computation of wastewater by difference using other measured or assigned quantities as detailed in Appendix B and summarized in Table 8. Essentially the overall material balance consists of four entering streams (refuse, sludge, fuel gas, and oxygen) and four exiting streams (ferrous metal, product gas, slag, and wastewater). The unreliable operation of the particulate recycle system resulted in two additional exit streams that are internal recycle streams under normal operation -- char from the scrubber and oil from the ESP. Operational data was collected to determine refuse, sludge, fuel gas, oxygen, ferrous metal, product gas, and slag rates. Char rates were measured periodically. Oil rates were not measured, but were estimated from previous experimental work since their small magnitude would have little effect on the material balances. Wastewater generation was computed by difference in the overall balance.

TABLE 8. OVERALL MASS BALANCE ASSUMPTIONS

(1) Product gas saturated with water at 21°C (70°F).

(2) Nitrogen and argon entering with oxygen leave in product gas.

(3) Char production computed from rate equation based on measurements over a range of operating rates.

C = -526.8 + 9.132 x (TPD)

C = lb/hr of dry char

TPD = operating rate in tons per day of feed

(4) ESP oil rate is 2% of operating rate

Component balances using measured data were attempted, but were found to be completely unsatisfactory. Balances could not be achieved on either the inorganic components or the carbon. It was apparent that the source of the problem was the refuse sampling prior to analysis. Clearly, a heterogeneous material such as refuse is extremely difficult to sample representatively. The test plan called for sampling on a limited basis only. The results of the component balances using this data indicated that the samples were not representative. To proceed with component balances required an additional set of assumptions (see Table B-3) which are detailed along with the component balances in Appendices B-H).

Table 9 presents a summary of the overall mass balance results for the seven test periods. Recall period 5 is a baseline, refuse only period and should be used for comparison. In general these results show little variation between operating in the codisposal mode and operating with refuse only.

Gas composition for each of the test periods are compared in Table 10. These compositions are all well within the range reported in Table 4 for refuse-only and display no significant departures from refuse-only compositions.

Overall heat balances for each test were computed to evaluate the efficiency of conversion of incoming materials into useful product gas. Obviously, the uncertainty in the refuse composition is also reflected as an uncertainty in the heating value of the incoming refuse. When the heating values measured for the actual refuse samples analyzed are used, a significant portion of the incoming energy is unaccounted for in the output streams. In order to obtain a reasonable measure of conversion efficiency, the assumptions detailed in Table 11 were used to compute conversion efficiencies based on total energy leaving the system. Table 12 presents a summary of the overall heat balances for the various test periods.

Table 13 summarizes the slag compositions obtained during the various test periods. The basic composition of the slag appears to remain fairly uniform within the previously noted range in Table 3. The trace components will be discussed in more detail in Section 12; however, it is interesting to note the substantial increase in nickel in periods 1, 2, 6, and 7 when raw primary sludge was used. This is believed to be related to the presence of industrial nickel alloying waste in the sludge from Huntington, West Virginia.

Tables 9, 10, 12, and 13 summarize the codisposal process. Comparisions between refuse-only (test 5), raw primary sludge (tests 1, 2, 6, and 7), and mixed sludge (tests 3 and 4) can be made. In general, the material balances, slag compositions, and gas compositions are quite similar in all three instances. The variation in conversion efficiency to gas shows, in one case with mixed sludge, an indication of less efficient operation. This poor efficiency suggests that inefficient heat transfer in the converter (channeling) was occurring. (See Section 10 for more detail).

TABLE 9. SUMMARY OF OVERALL MASS BALANCES

Stream	Test 1		Test 2		Test 3		Test 4		Test 5		Test 6		Test 7	
	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$	$\frac{Mg}{day}$	$\left(\frac{ton}{day}\right)$
Refuse	77.1	(85.0)	75.3	(83.0)	61.1	(67.3)	78.0	(86.0)	73.5	(81.0)	55.3	(61.0)	86.2	(95.0)
Sludge (wet)	5.1	(5.6)	7.3	(8.1)	9.1	(10.0)	10.5	(11.6)	-	-	3.4	(3.7)	20.1	(22.2)
Fuel Gas	1.3	(1.4)	1.2	(1.3)	1.3	(1.4)	1.7	(1.9)	1.7	(1.9)	1.7	(1.9)	1.7	(1.9)
Oxygen	14.1	(15.5)	15.6	(17.2)	17.4	(19.2)	16.1	(17.7)	15.1	(16.7)	12.9	(14.2)	19.1	(21.0)
Total In	97.6	(107.5)	99.4	(109.6)	88.9	(97.9)	106.3	(117.2)	90.3	(99.6)	73.3	(80.8)	127.1	(140.1)
Ferrous Metal	4.2	(4.6)	4.2	(4.6)	2.5	(2.8)	3.8	(4.2)	6.2	(6.8)	2.5	(2.8)	4.1	(4.5)
Product Gas	38.7	(42.7)	42.5	(46.9)	37.4	(41.2)	41.5	(45.7)	37.9	(41.8)	34.3	(37.8)	49.4	(54.5)
Slag	19.9	(21.9)	19.1	(21.1)	12.7	(14.0)	17.2	(19.0)	16.8	(18.5)	10.0	(11.0)	18.0	(19.8)
Char	3.4	(3.8)	3.4	(3.8)	2.1	(2.3)	4.2	(4.6)	2.5	(2.8)	0.9	(1.0)	6.1	(6.7)
Oil	1.6	(1.8)	1.6	(1.8)	1.4	(1.5)	1.8	(2.0)	1.5	(1.6)	1.2	(1.3)	2.1	(2.3)
Wastewater	29.8	(32.7)	28.6	(31.4)	32.8	(36.1)	37.8	(41.7)	25.4	(28.1)	24.4	(26.9)	47.4	(52.3)
Total Out	97.6	(107.5)	99.4	(109.6)	88.9	(97.9)	106.3	(117.2)	90.3	(99.6)	73.3	(80.8)	127.1	(140.1)

TABLE 10. SUMMARY OF PRODUCT GAS ANALYSES

Component	Mole Percents Test. 1 Vol. %	Test 2 Vol. %	Test 3 Vol. %	Test 4 Vol. %	Test 5 Vol. %	Test 6 Vol. %	Test 7 Vol. %
H_2	31.25	29.62	30.32	25.30	28.14	29.64	26.81
CO	36.24	36.80	31.56	36.72	37.28	33.74	34.19
CO_2	23.52	23.85	28.86	25.01	23.07	25.58	26.85
CH_4	4.46	5.02	4.82	6.48	6.21	5.89	6.12
C_2H_2	0.25	0.41	0.48	0.60	0.46	0.52	0.72
C_2H_4	1.32	1.68	0.68	2.26	1.90	1.91	2.19
C_2H_6	0.33	0.32	0.23	0.46	0.44	0.34	0.40
C_3H_6	0.27	0.23	0.20	0.39	0.32	0.27	0.28
C_3H_8	0.25	0.18	0.02	0.21	0.23	0.12	0.19
C_4*	0.47	0.34	0.23	0.44	0.40	0.28	0.40
C_5+	0.35	0.27	0.17	0.31	0.29	0.22	0.36
C_6H_6	0.17	0.25	0.22	0.26	0.24	0.26	0.34
HHC‡	0.32	0.29	0.12	0.23	0.26	0.17	0.37
H_2S	0.00	0.04	0.01	0.02	0.02	0.02	0.03
CH_3OH	0.14	0.08	0.12	0.11	0.11	0.04	0.09
O_2	0.05	0.03	0.24	0.26	0.03	0.04	0.04
Ar	0.62	0.59	0.74	0.95	0.59	0.61	0.63

* C_4 is a composite of butanes, butenes, butadiene, vinyl acetylene and diacetylene

+ C_5 is a composite of pentanes, pentenes, isoprene, and cyclopenetadiene

‡ HHC are higher hydrocarbons C6 and above excluding benzene

TABLE 11. OVERALL HEAT BALANCE ASSUMPTIONS

1. Refuse heating value (excluding heat from metal oxidation) is the average of measurements for test program 18.21 MJ/kg (7,831 Btu/lb) on dry basis.

2. Refuse moisture content taken from component mass balance.

3. Sludge higher heating value measured for representative sample from test period.

4. Fuel gas higher heating value is 46.78 MJ/Nm^3 (1,188 Btu/Sft^3) based on measured gas analysis.

5. Slag higher heating value is zero.

6. Slag exits hearth at 1,650°C (3,000°F).

7. Slag specific heat capacity is 1.21 kJ/kg-°C (0.29 Btu/lb-°F).

8. Product gas higher heating value is the mean of all samples taken during each period.

9. Char higher heating value is 21.76 MJ/kg (9,355 Btu/lb) on a dry basis.

10. ESP oil higher heating value is 32.5 MJ/kg (14,000 Btu/lb).

11. Hearth cooling loss is 1.4 GJ/hr (1.3×10^6 Btu/hr) based on measurements.

12. Converter shell heat loss is 0.35 GJ/hr (3.3×10^5 Btu/hr) based on calculations.

13. Heat lost in condensation during gas cleaning is 2.53 MJ/kg of wastewater (1,086 Btu/lb).

TABLE 12. SUMMARY OF OVERALL HEAT BALANCES

Energy Content GJ/day (million of Btu/day)

Stream	Test 1		Test 2		Test 3		Test 4		Test 5		Test 6		Test 7	
Refuse	960.5	(910.4)	953.5	(903.7)	667.5	(632.7)	902.2	(855.1)	827.9	(744.7)	619.6	(587.3)	1027.8	(974.2)
Sludge	19.4	(18.4)	21.4	(20.3)	28.4	(26.9)	33.6	(31.8)	-	-	10.7	(10.1)	53.0	(50.2)
Fuel Gas	68.4	(64.8)	63.4	(60.1)	68.4	(64.8)	92.7	(87.9)	92.7	(87.9)	92.7	(87.9)	92.7	(87.9)
Oxygen	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total In	1048.3	(993.6)	1038.3	(984.1)	764.3	(724.4	1028.5	(974.8)	920.6	(872.6)	723.0	(685.3)	1173.5	(1112.3)
Ferrous Metal	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Product Gas	499.6	(473.5)	543.4	(515.0)	419.6	(397.7)	535.5	(507.6)	507.6	(481.1)	433.2	(410.6)	637.8	(604.5)
Slag	39.4	(37.3)	38.0	(36.0)	25.2	(23.9)	34.2	(32.4)	33.2	(31.5)	19.8	(18.8)	35.7	(33.8)
Char	75.0	(75.0)	75.0	(71.1)	45.4	(43.0)	90.8	(86.1)	55.3	(52.4)	19.7	(18.7)	132.3	(125.4)
Oil	64.6	(61.2)	64.6	(61.2)	53.8	(51.0)	71.7	(68.0)	57.4	(54.4)	46.6	(44.2)	82.5	(78.2)
Wastewater	44.3	(42.0)	44.3	(42.0	47.3	(44.8)	56.1	(53.2)	38.4	(36.4)	38.4	(36.4)	73.9	(70.0)
Heat Losses	116.2	(110.1)	113.2	(107.3)	124.0	(117.5)	136.8	(129.7)	105.6	(100.1)	102.9	(97.5)	161.9	(152.7)
Total Out	839.0	(795.2)	878.4	(832.6)	715.2	(677.9)	925.1	(877.0	797.5	(755.9)	660.6	(625.7)	1123.2	(1064.6)
N_1*	59.5%		61.9%		58.7%		57.9%		63.6%		65.6%		56.8%	
N_2+	75.1%		76.8%		71.2%		74.4%		77.0%		74.8%		74.8%	

* Efficiency of conversion to gas based on total energy out as operated.

+ Efficiency of conversion to gas based on total energy out assuming recycle of particulate (char and oil).

TABLE 13. SUMMARY OF SLAG ANALYSES

Major Components	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
C (wt. %)	1.0	0.8	0.2	0.9	1.8	0.8	0.4
SiO_2	60.0	59.8	64.0	66.5	61.5	56.1	56.8
$Al_2 0_3$	10.0	11.9	11.0	10.5	11.6	9.7	9.3
C_aO	12.0	10.5	12.1	9.9	9.8	8.5	11.3
FeO	8.1	8.1	6.7	6.3	8.0	14.6	8.3
MgO	1.9	0.9	1.2	1.6	0.9	1.9	1.0
P_2O_5	0.9	0.6	0.6	0.8	0.6	0.4	0.8
BaO	0.2	0.2	0.1	0.1	0.1	0.1	0.2
MnO	0.2	0.1	0.3	0.2	0.2	0.3	0.2
Cr_2O_3	0.05	0.1	0.05	0.5	0.5	0.5	0.5
TiO_2	0.51	0.52	0.56	0.6	0.7	0.6	0.6
Ni_O	0.3	0.2	0.05	0.05	0.05	0.05	0.1
	95.16	93.72	96.86	97.95	95.75	93.55	90.4
Trace Components							
Cd (ppm)	10	10	6	5	5	5	5
Cr	891	645	363	3420	3420	3420	3420
Cu	4300	4000	3800	2860	4000	3400	3300
Fe	55000	53000	53000	48800	61970	113100	64300
Hg	0.01	0.02	0.01	0.05	0.03	0.01	0.15
Mn	1200	1700	1400	1140	1600	1300	1400
Ni	2700	1300	145	150	305	959	1500
Pb	119	119	128	120	94	75	243
Zn	455	482	456	350	309	404	1100

Improper blending of the wet sludge with refuse results in poor pellet formation during the feeding process using the existing equipment. Instead of being intimately mixed with the refuse to form a cohesive, stable particle, the slug of wet sludge acted as a lubricant for the pellet thus interfering in the bonding process which normally holds pellets together. This resulted in feeding loose, shredded refuse into the converter where its variable porosity and packing characteristics produced channeling of the hot hearth gas up through the bed without proper heat exchange with the charge. The loss of energy due to offgas temperatures in excess of 427 degrees C (800 degrees F) produced the observed decrease in conversion efficiency in these cases.

The detailed observations and calculation for each of the test periods are contained in Appendices B - H. Section 10 presents a discussion of general process-related observations. Section 11 details the calculational technique and projected results for operation in the normal mode with particulate recycle (char and ESP oil recycled to the hearth for gasification). Section 12 discusses the environmental emissions observed during the testing with particular emphasis upon the disposition of trace heavy metals. Section 13 presents some projected economics for the codisposal process as-practiced and also more favorable economics for a modified form of the process.

SECTION 10

CODISPOSAL PROCESS OBSERVATIONS

GAS PRODUCTION RATE

The methods used to calculate the gas production rate were described earlier. The gas production rates calculated per Mg (ton) of material fed are shown in Tables 14 and 15. Comparison of helium trace and pitot tube results shows that for all but one test period helium trace results were lower than pitot tube measurements. The inclusion of nitrogen and water vapor in the pitot tube results contributes to part of this difference. The gas production measured by pitot tube at ten minute intervals varied significantly. The standard deviation of the pitot tube results for different test periods varied between 53.15 and 97.46 Nm^3 per Mg (1,800 and 3,300 Sft^3 per ton) of feed. The standard deviation of helium trace results varied between 23.63 and 59.06 Nm^3 per Mg (800 and 2000 Sft^3 per ton).

TABLE 14. GAS PRODUCTION MEASURED BY HELIUM TRACE

Test Period	Number of Samples	Gas Production Per Unit of Feed Nm^3/Mg	Gas Production Per Unit of Feed $S\ ft^3/Ton$	Standard Deviation Nm^3/Mg	Standard Deviation $S\ ft^3/Ton$
5	6	437	14,800	24	800
1	3	402	13,600	38	1,300
2	6	440	14,900	53	1,800
6	9	490	16,600	59	2,000
7	14	396	13,400	41	1,400
3	12	452	15,300	53	1,800
4	6	396	13,400	44	1,500

TABLE 15. GAS PRODUCTION MEASURED BY PITOT TUBE

Test Period	Number of Samples	Gas Production Per Unit of Feed Nm^3/Mg	Sft^3/Ton	Standard Deviation Nm^3/Mg	Sft^3/Ton
5	12	325	11,000	97	3,300
1	No samples taken				
2	10	478	16,200	53	1,800
6	12	499	16,900	38	1,300
7	12	526	17,800	77	2,600
3	12	543	18,400	50	1,700
4	12	449	15,200	77	2,600

The fuel gas production rate will vary substantially as the gasifiable composition of the feed varies. High ash or water content will significantly reduce the gasifiable material available in a unit of feed. Comparisons of gas production rates based on the total feed can be misleading because of this effect. Comparison on a dry, ash free basis would be more meaningful. However, it was evident from the mass balances performed that a representative composition for the refuse was not obtained. Consequently, without an accurate set of refuse analyses to determine the gasifiable fraction of the feed, a reliable comparison could not be made. The gas production per Mg (ton) of gasifiable feed (organics on a dry, ash-free basis) is shown in Table 16 using the back-calculated refuse compositions to determine moisture and ash content. The results show variation similar to the gas samples per Mg (ton) of total feed.

TABLE 16. GAS PRODUCTION BASED ON GASIFIABLE MATERIAL

Test Period	Gas Production Per Unit of Feed Nm^3/Mg	Sft^3/Ton
5 (refuse only)	916	31,000
1 (refuse + primary)	859	29,100
2 (refuse + primary)	865	29,300
6 (refuse + primary)	1051	35,600
7 (refuse + primary)	913	30,900
3 (refuse + mixed)	1116	37,800
4 (refuse + mixed)	927	31,400

GAS HEATING VALUE

Product gas higher and lower heating values were calculated for each sample from the product gas analysis on a water, oxygen, and inert free basis. (Inerts include nitrogen, argon, and helium.) C_4 and higher hydrocarbons, except benzene, were lumped together as C_4's, C_5's and higher hydrocarbons (HHC) in the calculation. The mean gas higher heating value and standard deviation were calculated for each period, and these mean heating values were used in subsequent heat balances.

Gas heating value results were also reviewed, using several methods, for dependence on process variables. Sample results were divided into five groups, one group of samples from refuse-only operation (test period 5), two groups of samples taken during raw primary sludge processing (test period 2 was group 2 and test periods 1, 6, and 7 were group 3), and two groups of samples during mixed sludge processing (test period 3 was group 4 and test period 4 was group 5). Mean gas heating value and its standard deviation were calculated for each group. Two sample groups (groups number 2 and 4 in Table 17) exhibited significantly lower heating values than the other three. Investigation of operation during the periods associated with these two groups revealed the occurrence of significant periods of high offgas temperature suggesting refuse bed channeling which is believed to be caused by poor blending of high moisture sludge with refuse during feeding. To quantify the extent of this effect, the fraction of operating time the converter offgas was within different temperature bands was determined and plotted. Offgas temperature above 427 degrees C (800 degrees F) is considered evidence of channeling, and temperature above 538 degrees C (1000 degrees F) is evidence of serious channeling. The temperature records support the contention that channeling did occur at least 20% of the time in one case and 35% of the time in the other. Samples obtained during high offgas temperature periods exhibit lower mean heating value and higher standard deviation within a sample group than the other sets in Table 17. These two groups were judged unsuitable for use in subsequent study of heat value behavior.

For each sample group unaffected by high offgas temperature, higher heating value was plotted as a function of converter rate. The 95 percent confidence interval on the mean of all samples in the group was superimposed on each plot. The graphs are shown by Figures 18, 19, and 20 for refuse only, primary sludge, and mixed sludge respectively. Results indicate a trend toward higher gas heating values at higher converter rates. Though insufficient samples were taken at low rates to confirm this conclusion, such a trend is consistent with predicted converter behavior. Since converter heat losses are relatively constant, the portion of refuse combusted to cover these losses is constant as rate changes. This would predict more combustion in the hearth and a resultant lower product gas heating value at lower operating rates. More specific conclusions could not be substantiated with the available data.

TABLE 17. PRODUCT GAS HIGHER HEATING VALUE (HHV) COMPARISON

Sample Group	Feed	Number of Samples	Mean Higher Heating Value MJ/Nm^3 (Btu/Sft^3)	Standard Deviation MJ/Nm^3 (Btu/Sft^3)	95% Confidence Interval Lower Value MJ/Nm^3 (Btu/Sft^3)	95% Confidence Interval Upper Value MJ/Nm^3 (Btu/Sft^3)
1	Refuse	15	15.04 (381.9)	0.43 (10.8)	14.8 (376.8)	15.2 (387.0)
2	Refuse + Primary Sludge	12	14.11 (358.3)	0.82 (20.8)	13.7 (347.2)	14.5 (369.3)
3	Refuse + Primary Sludge	24	14.78 (375.3)	0.78 (19.7)	14.5 (368.1)	15.1 (382.5)
4	Refuse + Mixed Sludge	11	12.78 (324.4)	1.98 (50.4)	10.6 (269.9)	13.7 (349.0)
5	Refuse + Mixed Sludge	9	15.22 (386.6)	0.39 (18.5)	14.8 (375.1)	15.7 (398.1)

Samples taken at approximately the same rate, but while processing different feeds, were compared statistically. The comparisons between groups were made using the Student-t method assuming equal true means and equal true standard deviations. The t statistic was computed for comparing groups such as a and b. The t statistic is defined for such a comparison as $t = (X_a - X_b)/ S\,[(1/n_a) + (1/n_b)]^{1/2}$. The arithmetic mean of group a consisting of na observations is X_a. The square root of the pooled variance estimate is S which is given by $S^2 = [(n_a-1)\,S^2_a + (n_b-1)\,S^2_b]/[n_a + n_b - 2]$ where S_a is the standard deviation computed for group a. If the calculated t statistic is greater than the tabulated t statistic for a desired confidence level, then the assumption of equal true means is invalid. In this case where comparisons are being made between the mean heating values for various groups, if the computed t is less than the t value for the desired confidence level then the groups are not statistically different. These tests could not confirm a difference between any sample groups with a 97 percent confidence. Results indicate that at the sludge ratios tested, product gas higher heating value was unaffected by sludge processing. A summary of the statistical results is shown in Table 18.

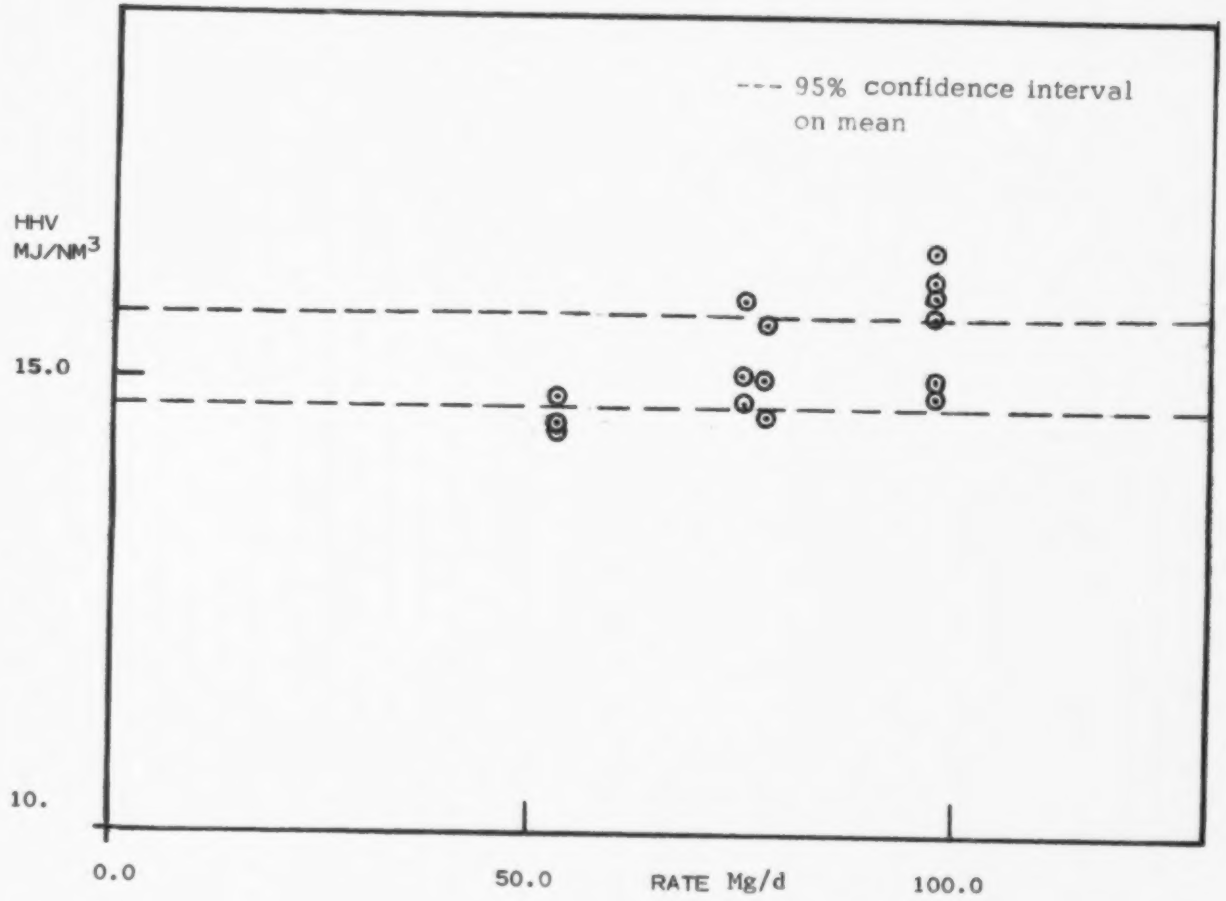

Figure 18. Product gas heating value - refuse only - vs. operating rate

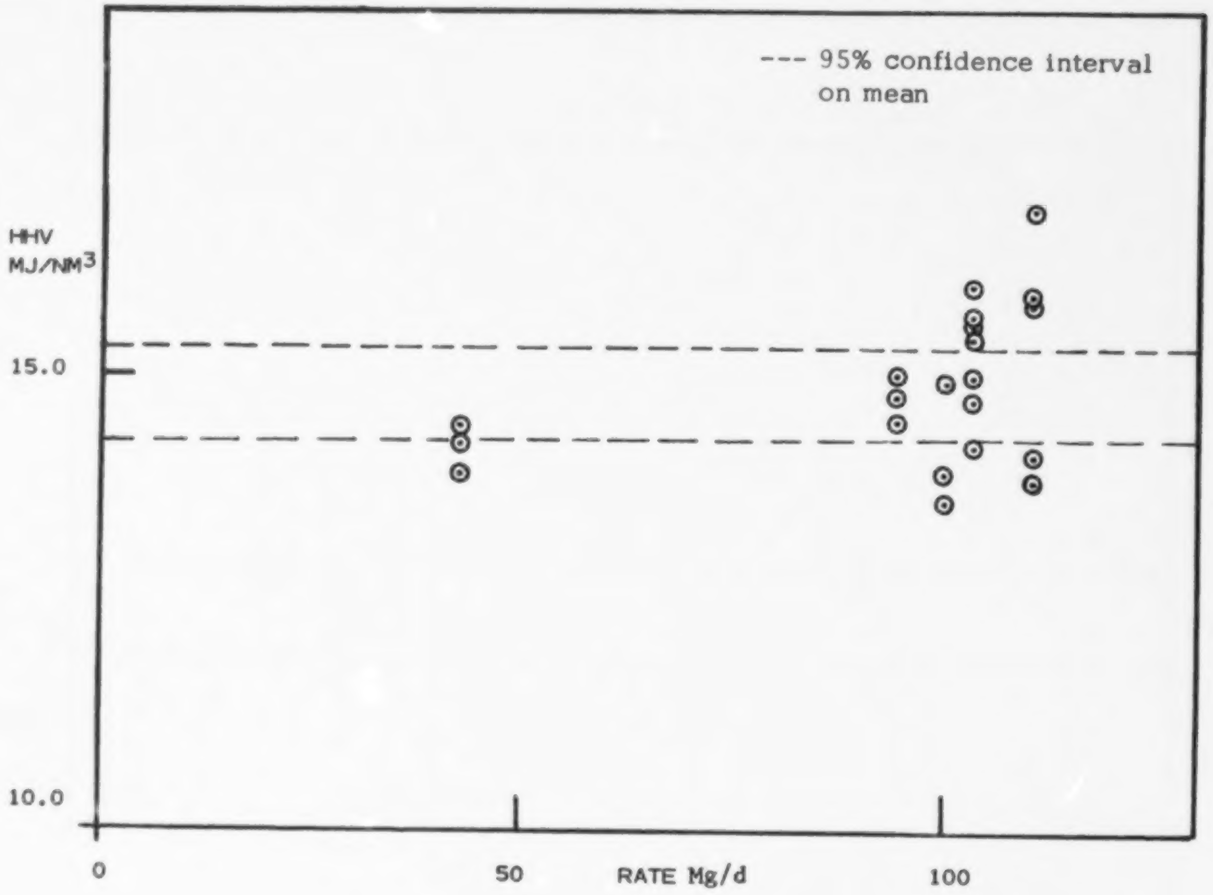

Figure 19. Product gas heating value - raw primary sludge - vs. operating rate

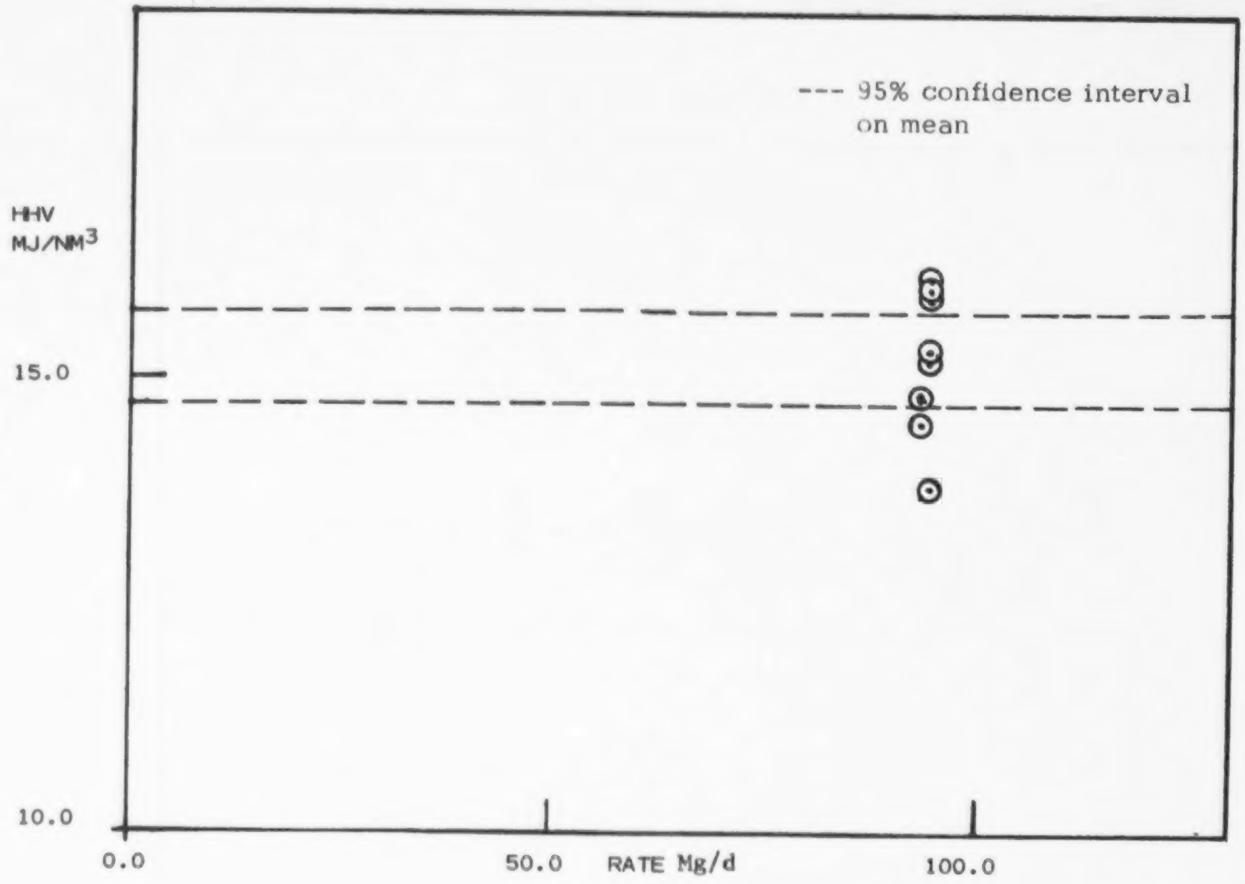

Figure 20. Product gas heating value mixed primary and secondary sludge - vs. operations rate

TABLE 18. STATISTICAL COMPARISON OF PRODUCT GAS HEATING VALUES

Sample Group	Number of Samples	Mean Higher Heating Value MJ/Nm^3 (Btu/Sft^3)	Standard Deviation MJ/Nm^3 (Btu/Sft^3)
Refuse Only (1)	6	15.3 (389.5)	0.39 (9.9)
Refuse + Primary Sludge (3)	15	14.7 (374.2)	0.72 (18.3)
Refuse + Mixed Sludge (5)	8	15.2 (386.6)	0.78 (19.8)

Groups Compared	Calculated t	t for 97.5 Percent Confidence Level
1 - 3	1.89	2.093
1 - 5	0.31	2.093
3 - 5	1.50	2.093

GAS PARTICULATE LOADING

The result from gas particulate sampling of the product gas after the condenser are shown in Table 19. The particulate loading and isokinetic variation (I = 100% at isokinetic flow condition) for each sample are listed. The particulate sample calculations have been corrected to remove the natural gas used to purge the ESP insulator compartments. The isokinetic variation is a measure of how close to isokinetic flow the sample was obtained. Isokinetic variation between 90 and 110 indicates an acceptable sample.

The particulate levels measured were all very low. The highest particulate level was 0.0449 g/Nm^3 (0.018 gr/Sft^3) measured during primary sludge processing at 106.3 Mg (117.2 tons) per day. Two samples had unacceptable values of I. For both samples I was below 90 which should cause too high a calculated particulate loading.

TABLE 19. PRODUCT GAS PARTICULATE LEVELS

Test Period	Type Feed	Particulate Loading g/Nm^3	gr/Sft^3	Isokinetic Variation
5	Refuse	0.0176	0.007	58.13
1	Refuse + Primary Sludge	No Sample Taken		
2	Refuse + Primary sludge	0.0372	0.015	102.5
6	Refuse + Primary Sludge	0.0223	0.009	92.26
7	Refuse + Primary Sludge	0.0449	0.018	86.93
3	Refuse + Mixed Sludge	0.0188	0.008	91.98
4	Refuse + Mixed Sludge	0.0201	0.008	91.70

The regulated particulate level for a stationary source is 0.18 g/Nm^3 (0.08 gr/Sft^3) corrected to 12% CO_2.* The regulated particulate level for a sludge incinerator is 0.65 g/kg of dry sludge input (1.3 lb/ton of dry sludge)+. These levels are applied to combustion products, so to compare requires putting the product gas numbers on a combustion product basis. This can be done by calculation to give the results indicated in Table 20. Table 21 presents the particulate loading based on the sludge incineration standard. Although two of the test periods (2 and 6) exceed the emission regulation, it should be recalled that this particulate is measured in the gas prior to combustion. If as little as 10% of the particulate is combustible, all the tests would fall below the regulated limit. The relatively high loading of particulate per unit of sludge processed is the result of the small fraction of sludge in the feed. At higher sludge-to-refuse ratios, the particulate loading calculated in this manner should be well below the regulated value.

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*(2) Federal Register, Vol. 36, No. 247, December 23, 1971.

+(3) "Background Information for New Source Performance Standards" (Vol. 3) EPA Report 450/2-74-003, APTP-1352 C (Feb. 1974).

TABLE 20. CALCULATED PARTICULATE LEVELS IN PUROX SYSTEM GAS COMBUSTION PRODUCTS AT 12 PERCENT CO_2*

Test Period	Particulate Level g/Nm^3	 gr/Sft^3
5 (Refuse)	0.0031	0.0013
1 (Primary)	-	-
2 (Primary)	0.0056	0.0023
6 (Primary)	0.0034	0.0014
7 (Primary)	0.0063	0.0026
3 (Secondary)	0.0031	0.0013
4 (Secondary)	0.0029	0.0012

* EPA regulation is 0.18 g/Nm^3 (0.08 gr/Sft^3) at 12% CO_2

TABLE 21. PARTICULATE LEVELS IN PRODUCT GAS BASED ON SLUDGE RATE*

Test Period	g/kg Sludge (ds)	Lb/ton Sludge (ds)
5	-	-
1	-	-
2	0.666+	1.332+
6	0.719+	1.438+
7	0.421	0.842
3	0.312	0.624
4	0.331	0.662

+If particulate is assumed to consist of at least 10% combustible material, these values will both be below the regulated limit.

* EPA Regulation is 0.65 g/kg (1.3 lb/ton) of dry sludge.

SECTION 11

PROJECTION OF RESULTS TO CASE OF PARTICULATE RECYCLE

The system performance expected with the recycle of particulate material and oil into the hearth combustion zone can be calculated from a heat balance on the hearth. The key assumption is that the additional energy required for the gasification of the recycled material is that needed to heat the material to 1650 degrees C (3000 degrees F), vaporize the water, and slag the ash. Pyrolysis reactions of the organic portion of the char and oil are assumed to have negligible heat requirements. The material is treated as a mixture of carbon, hydrogen, oxygen, water and ash. Since the amounts of oxygen and hydrogen in the recycled particulate are very small, they will be neglected in the model. Gasification of this material is carried out via the following reactions.

I $C + CO_2 = 2CO$ 23.618 MJ/kg (10,154 Btu/lb) of carbon

II $C + 1/2\ O_2 = CO$ - 9.187 MJ/kg (-3950 Btu/lb) of carbon

III $C + H_2O = CO + H_2$ 10.96 MJ/kg (4711 Btu/lb) of carbon

For simplicity, all the carbon in the particulate is assumed to be pyrolysis residue which will be gasified via Equations I, II or III. This will result in a higher level of carbon to be gasified than would actually occur because some carbon will be gasified as hydrocarbon in gaseous pyrolysis products.

An examination of the relative kinetics of reactions I, II and III is also required by this analysis. The carbon-oxygen reaction occurs rapidly at 1650 degrees C (3000 degrees F). The steam-carbon reaction, though slower than carbon-oxygen reaction II, is significantly faster than the carbon CO_2 reaction. With these rate considerations in mind, the process of gasification can be modeled as follows. Carbon will react via equations II and III. As long as sufficient water is available for reaction, carbon will react via equation III with heat required for reaction supplied by equation II. If insufficient water is available to consume all the carbon by reactions II and III, then reaction I will occur. To minimize the oxygen consumed, the quantity of carbon gasified by equation II will be just sufficient to heat the recycle stream and drive the alternate gasification reactions. The offgas composition is implicitly assumed to be similar to the gas measured.

The amounts of carbon gasified by reactions I, II and III can be computed from simple mass and heat balances on the recycled material. For the first step, assume no reaction via equation I. The carbon and heat balances are as follows:

$$C_{II} + C_{III} = T_C$$

$$(H_W)W + (H_A)A + C_{III}\ (4711) = C_{II}\ (3950)$$

T_C is total carbon; W is water; A is ash; H_W is heat to vaporize water; H_A is heat to melt ash. After solving for C_{II} and C_{III} the moles of C_{III} are compared to the moles of water available. If C_{III} is greater than W, then reaction I will occur and a different set of balances must be solved.

If reaction I is allowed to occur, assume reaction III goes to completion and all water available is consumed. The amount of carbon consumed by reaction III can then be related by stoichiometry to the water available as follows:

$$C_{III} = \frac{12}{18}(W)$$

The carbon and heat balances can now be reduced as follows:

$$C_I + C_{II} + \frac{12}{18}(W) = T_C$$

$$(H_W)W + (H_A)A + \frac{12}{18}(W)\ (4711) + C_I\ (10{,}154) = C_{II}\ (3950)$$

The solution of these balances allows the calculation of the additional gaseous product, additional oxygen consumed, and additional moisture in the product gas, if any. By applying these techniques to the material balances presented earlier, the effects of particulate recycle on process parameters can be predicted. Table 22 and 23 show the results of this analysis on the overall mass balances for each test period.

The oxygen consumption calculated for each test period is shown in Table 24. The oxygen use during test period 3 when offgas temperature was high, as a result of channeling, is significantly higher than that of the other tests. Oxygen consumption without particulate recycle is about 0.02-0.03 units of 0_2 per unit of feed less than the results in Table 24. The oxygen consumptions during other tests are in fairly good agreement.

TABLE 22. MATERIAL BALANCES WITH PARTICULATE RECYCLE (METRIC)
(Mg/Day)

Stream	Test 5	Test 1	Test 2	Test 6	Test 7	Test 3	Test 4
Refuse	73.5	77.1	76.3	55.3	86.2	61.1	78.0
Sludge	0	5.1	7.3	3.4	20.1	9.1	10.5
Fuel Gas*	1.7	1.3	1.2	1.7	1.7	1.3	1.7
Oxygen$^+$	17.3	16.9	18.4	14.2	23.7	19.4	19.2
Total In	92.5	100.4	102.2	74.6	131.7	90.9	109.4
Metal	6.2	4.2	4.2	2.5	4.1	2.5	3.8
PUROX Gas	44.5	46.9	50.7	37.8	62.3	43.2	51.0
Slag	17.8	21.2	20.5	10.3	20.3	13.5	18.9
Wastewater	24.0	28.1	26.8	24.0	46.0	31.7	35.7
Total Out	92.5	100.4	102.2	74.6	131.7	90.9	109.4

*Fuel gas is supplied to the hearth with the oxygen to preheat the oxygen to 3000 degrees F. Could be replaced by an equivalent Btu amount of PUROX System offgas.

+Oxygen is supplied at 97.5 percent purity. The balance is mostly argon with a trace of nitrogen.

TABLE 23. MATERIAL BALANCE RESULTS WITH PARTICULATE RECYCLE (ENGLISH)
(Tons per Day)

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Refuse	85.	83.	67.3	86.	81.	61.	95.
Sludge	5.6	8.1	10.0	11.6	0	3.7	22.2
Fuel Gas[*]	1.4	1.3	1.4	1.9	1.9	1.9	1.9
Oxygen[+]	18.6	20.3	21.4	21.2	19.1	15.6	26.1
Total	110.6	112.7	100.1	120.7	102.0	82.2	145.2
Metal	4.6	4.6	2.8	4.2	6.8	2.8	4.5
Offgas	51.7	55.9	47.6	56.2	49.	41.7	68.7
Slag	23.4	22.6	14.9	20.8	19.6	11.4	22.4
Water	30.9	29.6	34.8	39.5	26.6	26.3	49.6
Total	110.6	112.7	100.1	120.7	102.0	82.2	145.2

[*] Fuel gas is supplied to the hearth with the oxygen to preheat the oxygen to 3000 degrees F. Could be replaced by an equivalent Btu amount of PUROX System offgas.

[+] Oxygen is supplied at 97.5 percent purity. The balance is mostly argon with a trace of nitrogen.

TABLE 24. OXYGEN CONSUMPTION EXPECTED WITH PARTICULATE RECYCLE

Test Period	Mg O_2/Mg Total Feed
5	0.224
1	0.197
2	0.214
6	0.228
7	0.213
3	0.266
4	0.208

Table 25 presents a summary of the range of predicted oxygen consumptions measured when processing various types of feeds. Period number 3 was excluded due to the feeder problems discussed previously.

TABLE 25. OXYGEN CONSUMPTION RANGES WITH VARIOUS FEEDS

Type of Feed	Oxygen Consumption (Mg O_2/Mg Feed)
Refuse only	0.20 - 0.22
Refuse + primary sludge	0.20 - 0.23
Refuse + mixed sludge	0.21

The conclusion from these results is that over the range of sludge compositions and sludge fractions tested, there was no significant change in oxygen consumption.

The fuel gas production that was calculated assuming the model as described is shown in Table 26. Comparison with Table 14 indicates increases in gas production with particulate recycle of from 10-25 percent. The breadth of this range is a result of the range of operating rates and associated particulate production rates. Particulate recycle represents a significant portion of the total energy production from the PUROX System.

TABLE 26. GAS PRODUCTION EXPECTED WITH PARTICULATE RECYCLE

Test Period	Gas Production Nm^3/Mg	 Sft^3/Ton
5	514	17,400
1	487	16,500
2	526	17,800
6	543	18,400
7	502	17,000
3	526	17,800
4	490	16,600

The energy balance projections for particulate recycle operation are shown in Tables 27 and 28. As discussed earlier, the measured energy content of incoming refuse was high when compared to typical results. The variation in refuse composition and heating value was not adequately defined by the refuse samples taken. To compensate for the error induced by the unrepresentative refuse analysis, the efficiency of energy conversion was calculated based on the total energy leaving the process. The calculated efficiencies are all between 70 percent and 80 percent.

TABLE 27. ENERGY BALANCES WITH PARTICULATE RECYCLE (METRIC)
(GJ/Day)

	Test 5	Test 1	Test 2	Test 6	Test 7	Test 3	Test 4
Stream							
Refuse	827.9	960.5	981.9	619.6	1027.8	667.5	902.2
Sludge	0.0	19.4	21.4	10.7	53.0	28.4	37.4
Fuel Gas	92.7	68.4	63.4	92.7	92.7	68.4	53.2
Total In	920.6	1048.3	1066.7	723.0	1173.5	764.3	992.8
PUROX Gas	595.1	604.9	647.6	477.9	804.0	484.8	658.6
Slag	35.2	42.1	40.7	20.6	40.3	26.8	37.2
Wastewater	36.4	41.9	41.8	37.6	70.1	45.6	53.2
Heat Losses	105.6	116.2	113.2	102.9	161.1	124.0	136.8
Total Out	772.3	805.1	843.3	639.0	1075.5	681.2	885.8
Difference	148.3	243.2	223.4	84.0	98.0	83.1	107.0
Conversion Efficiency*	77.0%	75.1%	76.8%	74.8%	74.8%	71.2%	74.4%

* Based on heat out.

TABLE 28. ENERGY BALANCES WITH PARTICULATE RECYCLE (ENGLISH)
(Millions of Btu/Day)

Test Periods	Test 5	Test 1	Test 2	Test 6	Test 7	Test 3	Test 4
Stream							
Refuse	784.7	910.4	930.7	587.3	974.2	632.7	855.1
Sludge	0	18.4	20.3	10.1	50.2	26.9	35.5
Fuel Gas	87.9	64.8	60.1	87.9	87.9	64.8	50.4
Total In	872.6	993.6	984.1	685.3	1112.3	724.4	974.8
PUROX Gas	564.0	573.3	613.8	453.0	762.0	459.5	624.2
Slag	33.4	39.9	38.6	19.5	38.2	25.4	35.5
Wastewater	34.5	39.7	39.6	35.6	66.4	43.2	50.4
Heat Losses	100.1	110.1	107.3	97.5	152.7	117.5	129.7
Total Out	732.0	763.0	799.3	605.6	1019.3	645.6	839.8
Difference	140.6	230.6	184.8	79.7	93.0	78.8	135.0
Conversion Efficiency*	77.0%	75.1%	76.8%	74.8%	74.8%	71.2%	74.4%

* Based on heat out.

SECTION 12

ENVIRONMENTAL EFFECTS OF THE CODISPOSAL PROCESS

The environmental effects of refuse and sludge codisposal were estimated and compared with refuse only operation. The environmental effect of either type of operation is minimal. The estimate was based on the substances emitted to the environment from slag and in PUROX System gas combustion products.

Simple slag leaching tests were conducted using the procedure described in Section 8. The slag leachate obtained was analyzed by Union Carbide Corporation South Charleston Laboratories. Later samples were also analyzed by Union Carbide Corporation Tarrytown Laboratories because they could obtain lower detection limits for some analyses.

Since no standard currently exists for leachate quality, the analyses of the leachate samples by themselves have little meaning. However, for purposes of comparison, EPA standards for public drinking water supplies have been used to document the general overall superior quality of the leachate. Although the samples do slightly exceed some of the limits set down in the public drinking water standard, its very proximity suggests a minimal environmental effect upon the ground water. Earlier tests using slag from refuse-only operation indicate that the soil itself leaches substantially more material than the slag*.

The leachate samples prepared from slag obtained during the tests were analyzed by both laboratories. As can be seen from Table 29 the concentration of the trace components are essentially at or below the detection limits of the instrumentation used (see Appendix A for limits). The general proximity of the leachate to the public drinking water standard is strong evidence for the bound nature of the trace components in the slag.

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*(1) C. T. Moses, J. R. Rivero; "Design and Operation of the PUROX System Demonstration Plant", The Fifth National Congress on Waste Management Technology and Resource Recovery, Dallas, Texas, 1976.

TABLE 29. SLAG LEACHATE ANALYSES[*]

Analysis	Test 5[+]	Test 2[‡]	Test 6[+]	Test 7[+]	Test 3[‡]	Test 4[‡]	EPA Limit[#]
pH	7.7	-	7.8	7.85	7.85	7.7	
F^-	0.07 ppm	-	0.06 ppm	0.08 ppm	- ppm	- ppm	1.2 ppm
Cl^-	18.	4	4	4	4	3	-
P	0.2	2.0	0.7	0.6	1.0	1.0	-
As	BDL	BDL	BDL	BDL	BDL	BDL	0.05
Ba	BDL	BDL	0.09	0.10	BDL	BDL	1.10
Be	BDL	BDL	BDL	BDL	BDL	BDL	-
Cd	0.02	BDL	0.02	0.02	BDL	BDL	0.01
Cr	BDL	BDL	BDL	BDL	BDL	BDL	0.05
Cu	BDL	BDL	BDL	BDL	BDL	BDL	-
Hg	BDL	BDL	BDL	BDL	BDL	BDL	0.002
Fe	0.18	0.1	0.04	0.05	0.5	0.4	-
Pb	BDL	BDL	BDL	BDL	BDL	BDL	0.05
Mn	BDL	BDL	0.05	0.04	BDL	BDL	-
Ni	BDL	BDL	0.05	BDL	BDL	BDL	-
Zn	BDL	BDL	BDL	BDL	BDL	BDL	-
Ag	0.1	BDL	0.1	0.1	BDL	BDL	0.05

Below Detection Limit = BDL - See Appendix A for detection limits

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[*] No sample taken during test period 1

[+] Analysis by Union Carbide Corporation Tarrytown Laboratories

[‡] Analysis by Union Carbide Corporation South Charleston Laboratories

[#] (4) Federal Register, Vol. 40, No. 248, December 24, 1975.

The product gas particulate level was measured during all test periods except one, and the levels are shown in Table 19. Particulate levels were low during all periods and ranged from 0.0176 g/Nm^3 (0.007 gr/Sft^3) to 0.0449 g/Nm^3 (0.018 gr/Sft^3). The isokinetic variation of two samples was below the acceptable range of 90-110 percent and these two samples are not reliable. The measured particulate level was converted to particulate in the gas combustion products on a 12 percent CO_2 basis and the calculated particulate levels are shown in Table 20. The dry catch obtained during test periods 5, 6 and 7 were analyzed for trace metals and the results are shown in Table 30.

The product gas particulate sample collected during the refuse only test (period 5) produced an isokinetic factor (I) of 58.13. This value of I was well below the acceptable level, but no other data for this test period was available. The particulate level was 0.017 g/Nm^3 (0.007 gr/Sft^3) in the product gas which was equivalent to 0.0031 g/Nm^3 (0.0013 gr/Sft^3) in the gas combustion products. The low value of I was caused by a procedural error during sample collection. Particulate samples collected during an earlier refuse only run resulted in a particulate level of 0.023 g/Nm^3 (0.0094 gr/Sft^3) in the product gas.

Three particulate samples were taken during mixed sludge tests (periods #2, 6 & 7). Particulate loadings of 0.036, 0.022, 0.044 g/Nm^3 (0.015, 0.009 and 0.018 gr/Sft^3) were measured, and they are equivalent to 0.0056, 0.0034, and 0.0063 g/Nm^3 (0.0023, 0.0014 and 0.0026 gr/Sft^3) in combustion products at 12 percent CO_2. The samples were taken at system rates between 77.1 and 112.4 Mg (85 and 102 tons) per day. The third sample, taken at 90.7 Mg (100 tons) per day, has a calculated isokinetic factor of 86.9 which was slightly below the acceptable range. The isokinetic factor was satisfactory for the other samples.

Particulate measurements were obtained during mixed sludge processing at 78.9 and 91.6 Mg (87 and 101 tons) per day. The measured particulate concentration was 0.019 g/Nm^3 (0.008 gr/Sft^3) during both period 3 and 4. The calculated combustion product particulate level was 0.0031 g/Nm^3 (0.0013 gr/Sft^3) for the 78.9 Mg (87 tons) per day sample and 0.0029 g/Nm^3 (0.0012 gr/Sft^3) for the 91.6 Mg (101 tons) per day sample.

The results of the particulate sample analyses are shown in Table 30. The reported results have been converted to a mean metals concentration in the product gas, expressed in μg of metal per cubic meter of gas at standard conditions. The equivalent concentration in gas combustion products is also tabulated. Using the results, the metal emitted in the product gas during one day of operation was estimated. These estimates are summarized in Table 31. Only the metal which was contained in the particulate is included in this calculation.

TABLE 30. CONCENTRATION OF METAL IN PUROX SYSTEM GAS

Component	Product Gas ($\mu g/Nm^3$)**	Combustion Products ($\mu g/Nm^3$ @ 12 percent CO_2)**
As	4.6	0.60
Ba	0.65	0.09
Be	0.28	0.04
Cd	0.46	0.06
Cr	5.4	0.71
Ca	74	9.7
Fe	229	30.0
Hg*	-	-
Mn	2.8	0.37
Ni	14.6	1.9
Pb	12.4	1.6
Zn	72	9.4

*Insufficient amount of material available to analyze.
** 1 $\mu g/Nm^3 = 4.13 \times 10^{-7}$ gr/Sft^3

TABLE 31. GRAMS OF METAL EMITTED IN PUROX SYSTEM GAS

Basis: 1 day

Test Period Metal	5	6	7
As	0.10	0.21	0.28
Ba	0.31	0.02	0.02
Cd	0.04	0.02	0.03
Cr	0.38	0.20	0.19
Pb	0.76	0.47	0.38
System Rate Mg (tons) Per Day	52.6 (58)	77.1 (85)	90.7 (100)

As noted earlier, recirculation of scrubber water was not achieved during the codisposal tests as a result of mechanical problems with the particulate recycle system. This resulted in a significant dilution of the wastewater stream due to the continuous addition of about 0.38 m^3 per minute (100 gallons per minute) of makeup to the scrubbing system or a dilution factor at a 90.7 Mg per day (100 tons per day) operating rate of ~20 to 1. Since this was the only wastewater available, treatability tests were conducted with this material using two liter, continuous flow reactors to determine the kinetics of activated sludge treatment of this wastewater. The general conclusion of the treatability work was that 95% reductions in biological oxygen demand (BOD) can be achieved readily at this dilution. Table 32 presents a summary of typical wastewater properties and reactor operating parameters from the treatability tests.

TABLE 32. PUROX SYSTEM WASTEWATER TREATABILITY DATA

Wastewater Analysis		Reactor Operating Conditions	
$TBOD_5$	1350 ppm	$F/M \frac{BOD_5/day}{MLVSS}$	0.68
$SBOD_5$	1321 ppm	t_d, days	1.18
TCOD	3078 ppm	MLVSS, ppm	1684
SCOD	3012 ppm	So ($TBOD_5$), ppm	1350
COD/BOD_5	2.28	Se ($SBOD_5$), ppm	59

These results with wastewater from sludge codisposal confirmed earlier treatability studies which generally showed no technical problem in treating wastewater from the PUROX System. It has been recognized that significant economies will be realized by using municipal sewage as a source of dilution water since its relatively low BOD_5 (200 ppm) and significant content of nutrients will enhance treatment of PUROX System wastewater in a commercial installation. The treated waste stream could then be discharged back into the sewer main for final disposal. Removal of heavy metals from the PUROX System wastewater stream would be achieved by precipitation prior to treatment if that is necessary.

After the conclusion of the codisposal program in June 1977, operation of the PUROX System plant using refuse only continued throughout the summer. During this time significant improvements were made in the mechanical equipment utilized for particulate (char) recycle resulting in successful operation of the system. Data similar to that described in this codisposal program was collected and analyzed to evaluate overall system performance under these conditions.

In terms of overall process performance, the heat and material balances are in general agreement with the projected performance for refuse-only discussed in Section 11. Oxygen consumption and product gas generation are in good agreement with the calculated results as would be expected. These results suggest that the codisposal results with particulate recycle would also agree well with the projected results discussed earlier.

The question of environmental effects during particulate recycle, especially the ultimate disposition of heavy metals, was not addressed during the earlier discussion since it was felt this could only be satisfactorily answered by experimental measurement. These experimental measurements were made during the particulate recycle testing with refuse only subsequent to the codisposal program. The similarity of the refuse-only experimental particulate recycle results to those projected for refuse-only indicates a high probability that the projections for codisposal with particulate recycle would agree well with the actual results. In particular, the environmental effects reported here for refuse-only with particulate recycle should be expected also in the codisposal case. The trace metal balances for the various test periods in Appendices B-H indicate that the actual quantity of metals in the sludge is of the same order as that in the refuse. This suggests that test data from refuse only periods would provide considerable insight into metal disposition with sludge/refuse mixtures.

During the refuse-only, particulate recycle test, samples of the three effluent process streams (product gas, slag, and wastewater) were collected and analyzed for trace metals since it was felt that the handling of these materials represents the greatest environmental challenge to any disposal process. During the period the data in Table 33 were collected, operating problems with the scrubber and electrostatic precipitator resulted in performance at non-optimum levels, with particulate levels an order of magnitude higher than those reported in Table 19 (although still well below the Environmental Protection Agency regulation). In spite of this problem, no undesirable metal concentrations were found in the combustion products when combusted at the 12% CO_2 level. Table 34 presents a comparison between the trace metal concentrations in the combustion products of product gas obtained during particulate recycle with the time-weighted-average (TWA) threshold level values (TLV) currently regulated. The regulated levels in Table 34 are taken from the American Conference of Industrial Governmental Hygienists and represent the current status of regulation for trace metals in the work place. They are not strictly applicable to stack emissions.

TABLE 33. PRODUCT STREAM TRACE METAL CONCENTRATIONS WITH PARTICULATE RECYCLE

	Effluent Stream Concentration		
Metal	Product Gas*	Slag	Wastewater
Cd	0.017 ppm	9 ppm	0.22 ppm
Cr	0.069	322	0.07
Cu	0.60	3600	0.12
Fe	12.4	57000	39.9
Hg	0.064	0.88	0.02
Mn	0.091	3500	19.9
Ni	0.44	176	0.11
Pb	0.29	204	43.0
Zn	3.6	962	83.7

*Computed for metal content measured on isokinetically collected particles.

TABLE 34. TRACE METAL CONCENTRATIONS IN PRODUCT GAS COMBUSTION PRODUCTS

	Combustion Product Concentration (mg/ m^3, dry @ 12 percent CO_2)*		
Metal	Refuse +	Refuse + Sludge ‡ (~5% sludge (ds)/refuse)	TLV-TWA # (mg/ m^3) +
Cd	0.0022 mg/ m^3	0.0001 mg/ m^3	0.05 mg/ m^3
Cr	0.0090	0.0007	0.5
Cu	0.079	0.0097	0.2
Fe	1.62	0.03	5
Hg	0.0084	below detection limit	0.05
Mn	0.012	0.0004	5
Ni	0.058	0.002	1
Pb	0.038	0.002	0.15
Zn	0.47	0.009	5

*Computed from metal content in isokinetically collected particulate in the product gas.

+Refuse-only with particulate recycle and non-optimum gas cleaning.

‡Based on average of measurements using primary and secondary sludges with more optimum gas cleaning performance.

#ACGIH, National Safety News, pp. 83-93, September, 1977.

As can be seen from Table 34, even under non-standard operating conditions, the net emission of metals is well below the regulated levels.

Trace metals in the product gas have been detected on the small amount of entrained particulate that remains in the gas following the gas cleaning step. Vaporized metals in the gas can be neglected based on the following considerations. The low vapor pressures of the trace metals at the exit conditions of 38 degrees C and 10,133 Pa (100 degrees F and 1 atm) are indicated in Table 35. Vapor pressures are listed for the reduced metals and some of the chloride salts. If the partial pressure is taken as the vapor pressure (generally the partial pressure is less than the vapor pressure), maximum gas phase concentrations can be estimated as shown in Table 35. The levels shown are essentially all below detection limits except for mercury and mercuric chloride ($HgCl_2$). Although direct measurements have not been made, an estimate of the concentration can be obtained by considering the total amount of mercury entering with the refuse feed. Measurements made during 1977 testing indicate a maximum mercury concentration in the refuse of 0.05 ppm. If all this mercury were to end up in the product gas as vapor (an unlikely event as later discussion will indicate) the resulting concentration of mercury vapor in the product gas prior to combustion would be less than 0.08 ppm. After combustion at standard conditions of 12% CO_2, this translates to about 0.01 ppm in the combustion products which is well within the regulated value. An upper limit on mercury concentration in the feed can be estimated using the TLV value of 0.05 Mg/m^3. Based on this TLV, the maximum allowable mercury level in the feed to the PUROX System would be 0.22 ppm if the disposition is assumed to follow a similar pattern of all ending up in the gas (see Table 33). Based on these considerations, the trace metal content of the particulate was judged to be the only significant emission of metals in the gas phase.

The wastewater contains a significant amount of trace metals as can be seen from Table 36. Since the organic content of this stream is also significant, it will be processed through an activated sludge wastewater treatment plant to reduce the organic content to an acceptable discharge level. Pretreatment regulations for wastewater treatment plants are currently being prepared by regulating agencies. Although these pretreatment regulations have not been formally issued, the pretreatment requirements shown in Table 36 represent current thinking regarding acceptable heavy metal concentrations. These requirements can be readily met through the use of a simple chemical precipitation technique such as CaO addition. The metals are then essentially removed from the water phase and concentrated in a small amount of chemical sludge as insoluble hydroxides. This small quantity of sludge can be either recycled to the hearth of the converter where it will become part of the slag or it can be disposed of in a approved chemical landfill depending upon the relative cost of either approach. As can be seen from Table 36, chemical precipitation essentially reduces the heavy metal content of the wastewater to the analytical detection limits based upon solubility product calculations.

TABLE 35. TRACE METAL VAPOR PRESSURES AND MAXIMUM GAS CONCENTRATIONS

Component	Vapor Pressure* 38 degrees C (100 degrees F)	Maximum Gas Vapor Concentration 38 degrees C, 10,133 Pa (100 degrees F, 1 atm.)
Cd	$< 10^{-12}$ atm.	$< 10^{-6}$ ppm by weight
Cr	$< 10^{-12}$	$< 10^{-6}$
Cu	$< 10^{-12}$	$< 10^{-6}$
Fe	$< 10^{-12}$	$< 10^{-6}$
Hg	$< 7 \times 10^{-6}$	56
Mn	$< 10^{-12}$	$< 10^{-6}$
Ni	$< 10^{-12}$	$< 10^{-6}$
Pb	$< 10^{-12}$	$< 10^{-6}$
Zn	$< 10^{-12}$	$< 10^{-6}$
Cu_2Cl_2	10^{-12}	10^{-6}
$FeCl_2$	$< 10^{-12}$	$< 10^{-6}$
Hg_2Cl_2	10^{-10}	0.002
$HgCl_2$	10^{-7}	1
$PbCl_2$	$< 10^{-12}$	$< 10^{-6}$

*(6) Lange's Handbook of Chemistry, 11th ed., McGraw-Hill (1973).

TABLE 36. WASTEWATER METAL CONCENTRATION FROM REFUSE ONLY OPERATION WITH PARTICULATE RECYCLE

Metal	Raw Wastewater	Wastewater and Precipitation*	Pretreatment Requirement
Cd	0.22 ppm	0.07 ppm	0.1 ppm
Cr	<0.07	< 0.04	1.0
Cu	0.12	< 0.04	0.5
Fe	39.9	0.04	20.0
Pb	43.0	< 0.05	0.5
Mn	19.9	1.0	1.0
Ni	0.11	< 0.04	5.0
Zn	83.7	< 0.03	5.0
Hg	<0.02	< 0.003	0.02

*These values are essentially the detection limits for these metals where a < sign is used. Based on solubility calculation for hydroxides at pH 10.

The slag concentration of trace metals with particulate recycle is compared in Table 37 with the slag obtained using refuse-only without particulate recycle and slag from refuse plus sludge tests. Significantly, the Pb, Zn, Cd and Hg all show substantial increases following particulate recycle to the hearth adding support to the mechanism of heavy metal capture in the slag phase. Although leaching tests were not conducted using the slag from the particulate recycle period, there is no reason to expect that its excellent non-leaching properties would differ significantly from the results previously reported.

Table 38 indicates that certain volatile metals (Cd, Pb, Zn, and Hg) are less effectively retained in the slag than other less volatile metals (Cr, Cu, Fe and Ni). However, the relatively low product gas temperature combined with the efficient gas cleaning in the scrubber and ESP results in a very small amount of these metals being lost into the product gas. The combination of efficient particulate removals from the product gas and the approximately ten-fold dilution of the gas during combustion diminishes the stack emission levels to a point far below that for typical incineration devices. The net result is a minimal potential hazard from stack emission of trace metals.

The mechanism of capture of these volatile metals in the slag as indicated in the data here is believed to be related to the formation of relatively stable inorganic salts which become physico-chemically bonded within the silicate matrix of the slag. Of the metals not in the slag, all but Hg are essentially in the wastewater where they can be easily separated. The actual amount of Hg is so very low that the 15% of the total that does leave with the gas in the particulate results in a combustion product emission that is an order of magnitude below the regulated limit. Further cleaning of the gas could remove most of the residual amount if it is required.

The overall conclusion from this initial examination of data from refuse-only operation with particulate recycle indicates an environmentally sound handling of the trace metals in the PUROX System.

TABLE 37. TRACE METAL CONCENTRATIONS IN SLAG

Metal	Refuse	Refuse + primary sludge [~5% sludge(ds)/refuse]		Refuse + mixed sludge [~5% sludge (ds)/refuse]	Refuse [Particulate Recycle]
			Range		
Cd	5.4 ppm	7 ppm	(5-9) ppm	8 ppm	9 ppm
Cr	3400	2081	(650-3400)	1853	322
Cu	4000	3771	(3300-4300)	3338	3600
Fe	61935	71672	(53000-114000)	51053	57000
Hg	0.3	5	(0.02-10)	0.03	0.88
Mn	1600	1399	(1200-1700)	1274	3500
Ni	304	1614	(960-2700)	174	3500
Pb	95	141	(80-240)	118	204
Zn	310	609	(400-1100)	403	962

TABLE 38. TRACE METAL DISPOSITION IN PROCESS EFFLUENT STREAMS

Metal	Percent of Total Metal Emitted in Product Gas Before Combustion	Percent of Total Metal Emitted in Slag	Percent of Total Metal Emitted In Wastewater*
Cd	0.50 percent	96.4 percent	3.10 percent
Cr	0.05	99.92	0.03
Cu	0.04	99.95	0.01
Fe	0.05	99.85	0.10
Pb	0.30	77.60	22.10
Mn	-	99.20	0.80
Ni	0.60	99.30	0.10
Zn	0.80	88.70	10.50
Hg	15.0	82.50	2.50

* Trace metals would be precipitated prior to wastewater treatment.

SECTION 13

PROJECTED ECONOMICS OF THE CODISPOSAL PROCESS

The test program conducted at the South Charleston PUROX facility determined the performance of the PUROX System while processing relatively dry sludge to refuse ratios (about 0.075) and modest solids contents (15 to 30%) in the sludge. These conditions are appropriate for a community with a small amount of sludge to dispose of 45-63 Mg (50 to 70 tons) per day of dry sludge and access to a substantial supply of refuse. Under these conditions of operation, the PUROX facility economics are basically determined by the alternatives open to the community for refuse disposal. Only if the refuse disposal economics are attractive will the sludge disposal be attractive.

For the economics to become less dependent on the allowable cost of refuse disposal the ratio of dry sludge to refuse must be increased. Under these conditions the economics become more sensitive to the economics of sludge disposal. It further has the advantage that larger quantities of sludge can be disposed of in a facility of reasonable size. Less refuse is needed and the allowable cost of disposal of refuse becomes less critical to the overall economic attractiveness.

Projections of sludge disposal costs are provided for facilities processing four different sludge solids contents (cases A-D). Case A is based on sludge dewatered to 20 percent solids and delivery of the 20 percent sludge cake to the PUROX facility. Case B is based on sludge dewatered to 25 percent solids and delivery of the sludge cake to the PUROX facility. For these cases, the PUROX facility is operated in a similar manner to the test program in which separately dewatered sludge is fed to the converter along with municipal refuse.

Economics and practical considerations favor removing as much moisture as is reasonable in a combination of dewatering and drying steps before introduction of the sludge with refuse into the PUROX converter. This minimizes use of the PUROX converter and gas cleaning capacity for processing moisture. It maximizes the use of the PUROX System capacity for the critical task of producing energy and disposing of the sludge solids. Cases C and D are included in the projections of sludge disposal costs to reflect improvements in the codisposal process, as compared to that which practiced at South Charleston.

Case C is based on delivery of 3 percent sludge solids to the PUROX facility. At the facility, the 3 percent sludge solids would be combined with the PUROX System scrubber slurry and jointly dewatered to 35 percent solids with a belt filter press. The scrubber slurry contains char, produced from the pyrolysis of refuse and sludge, which enhances the dewatering characteristics of sludge. Bench scale evaluations of the dewaterability of the char and sludge mixture have shown significantly reduced polymer requirements from that of separate sludge dewatering and substantially higher cake solids following the filtering process.

Case D is based on codewatering of sludge and char to 35 percent as in Case C and drying the 35 percent cake solids in a separate dryer to approximately 70 percent solids. In cases C and D the char/sludge mixture, after dewatering (and drying in Case D), is fed into the converter together with municipal refuse. To properly compare these cases, all costs associated with dewatering from 3 percent solids and ultimately disposing of the sludge have been included. Dewatering costs were taken from published literature as $55 to $66 per dry Mg ($50 to $60 per dry ton) for dewatering from 3 percent to 25 percent solids.*

Table 39 is provided to identify: capital equipment and costs, amortization of capital cost, annual operating costs and revenues, and the net sludge disposal cost for a facility designed to codewater, dry and process 363 dry Mg (400 dry tons) of sludge per day (Case D). The ratio of dry sludge to as-received refuse is 0.30. The capital and operating costs are estimates based on recent proposals submitted by Union Carbide and recent price quotes from filter press and dryer equipment manufacturers.

The estimated net sludge disposal cost of $44/dry Mg ($40/dry ton) is based on assumed facility revenues from the sale of fuel gas at $2.23/GJ ($2.35/MM Btu), the sale of ferrous metal at $44/Mg ($40/ton), and a refuse disposal fee of $16.50/Mg ($15.00/ton) of as-received refuse.

The PUROX System includes the equipment required for gasification of the feed material and gas cleaning. The oxygen plant includes the equipment required to supply high purity oxygen to the PUROX System converters. The wastewater pretreatment system includes equipment for storing and adjusting the pH of the PUROX System wastewater prior to discharge. The wastewater is assumed to be returned, based on a diurnal cycle, to the wastewater treatment plant. Minimal costs are anticipated for the diurnal treatment of the wastewater; therefore, no costs were allocated in the projected economics.

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*(7) Van Note, R.H., et al, "A Guide to the Selection of Cost Effective Wastewater Treatment Systems," EPA-430/9-75-002, July, 1975

TABLE 39. ESTIMATED ECONOMICS - PUROX CODISPOSAL FACILITY

Design Capacity: 363 dry Mg of sludge/day
(400 dry tons of sludge/day)
dry sludge to refuse ratio of 0.30

Capital Costs (in thousands of dollars)	
PUROX System, Oxygen Plant, Wastewater Pretreatment System	57,000
Front End System	15,000
Site Facilities	13,000
Buildings and Site Improvements	4,000
Codewatering and Drying Equipment	22,000
TOTAL	111,000
Annual Operating Costs (in thousands of dollars)	
Facility Operation and Maintenance	6,370
Facility Power and Miscellaneous Production Material	7,330
Levelized Amortization of Capital	10,500
TOTAL	24200
Annual Revenues (in thousands of dollars)	
Refuse Disposal	7,870
Fuel Gas	9000
Ferrous Metal	1470
TOTAL	18340
Annual Sludge Disposal Cost (in thousands of dollars)	5860
Net Sludge Disposal Cost	$44/Mg of dry sludge ($40/Ton) of dry sludge

In this case of 363 Mg/day (400 tons/day) of dry sludge at a sludge dry solids to refuse ratio of 0.30, 807.8 m^3/day (213,400 gal/day) of wastewater with a BOD_5 load of about 30,000 ppm would be returned to the adjacent wastewater treatment plant which was producing the 363 dry Mg (400 dry tons) per day of sludge. If it is assumed that about 0.9 Mg (1.0 ton) of dry sludge is produced from 3785 m^3 (10^6 gallons) of wastewater, with an influent concentration of 200 ppm BOD_5, then the wastewater treatment plant will handle a flow of 1.514×10^6 m^3/day (400×10^6 gal/day). The total BOD_5 into the wastewater plant (excluding the PUROX System flow is 302.8 Mg/day (333.8 tons/day). The BOD_5 from the PUROX System codisposal operation would add 24.2 Mg/day. This represents an 8.0 percent increase in load on the wastewater treatment plant. Since wastewater plants are sized with about 30 percent additional capacity to handle diurnal variations, storage of the PUROX wastewater for addition at appropriate times in the diurnal cycle could be accomplished with minimal cost.

The front end system includes equipment for refuse receiving, storing, shredding, magnetic metal separation and delivery to the PUROX System. Site facilities include the PUROX System control building, electrical power distribution equipment, process and utility interconnecting piping, cooling water system, a fuel gas compression system to compress the PUROX System fuel gas to 207 KPa (30 psig), and a process steam boiler. Buildings and site improvements include personnel and administrative buildings and site preparation prior to construction. The codewatering and drying equipment include belt filter presses for codewatering the char sludge mixture to 35 percent solids, dryers to dry the mixture to 70 percent solids, and sludge conveying equipment.

The facility annual operating costs include operating labor and supervision, maintenance, facility power at $.03/KWHR, miscellaneous production materials and the amortization of the capital cost at 7% for 20 years.

Figures 21 through 32 are provided to illustrate estimated net sludge disposal costs for various sludge solids contents, refuse disposal fees, and facility throughputs. The net sludge disposal cost is the difference between total facility capital and operating costs and facility revenues expressed in dollars per dry Mg or dollars per dry ton. The cost includes dewatering (from 3% clarifier solids), processing, and ultimately disposing of a dry Mg or dry ton of municipal sludge at the PUROX facility. The estimated net sludge disposal costs for all the figures were calculated in the same manner and with the same assumptions of electric power costs, and amortization rate as in Table 39.

The figures are based on processing three different sludge to refuse ratios: 0.05, 0.3, and 0.6. The net sludge disposal cost for each of the three ratios is shown on the basis of refuse disposal fees of $5.50/Mg

($5.00/ton) and $16.50/Mg ($15/ton) of as-received refuse. The revenues from the fuel gas and ferrous metal sales are based on the assumptions used in Table 39.

All cost estimates and economic projections of sludge disposal costs (1977 dollars) are budgetary based on general design information. Site and project-specific costs such as financing costs, capital escalation and interest during project construction, land cost, insurance cost, consulting fees and miscellaneous legal fees are not included.

The sensitivity of the sludge disposal costs to the allowable refuse disposal fee is illustrated in Figures 21-32. At very low dry sludge to refuse ratios refuse disposal economics control rather than those of sludge disposal. If a refuse-only facility can be economically justified then sludge can be disposed in the facility with very attractive disposal costs. If refuse-only cannot be justified the relatively small amount of sludge represented by a 0.05 dry sludge to refuse ratio will not appreciably alter the overall economics. This is illustrated by comparing the sludge disposal cost for allowable refuse disposal costs of $5.50 and $16.50 per Mg ($5 and $15 per ton).

Figures 21-24 illustrate the economics of sludge disposal based on a sludge-to-refuse ratio of 0.05 which is equivalent to the national per capita ratio of sludge generation to refuse generation. Figures 25-32 illustrate the economics of sludge disposal based on operating at a higher sludge (dry solids)-to-refuse ratio than the national per capita. Many municipalities may require a higher sludge-to-refuse processing ratio because of limited refuse availability at a given site (generally below 1814 Mg (2000 tons) per day) and large quantities of wastewater processed in one wastewater treatment facility. Figures 25-28 are provided to indicate estimated sludge disposal costs for a 0.30 ratio of sludge-(dry solids)-to-refuse. Figures 29-32 are provided to indicate estimated sludge disposal costs for a 0.6 ratio of sludge-(dry) solids)-to-refuse. At these ratios, large quantities of sludge can be processed with substantial redúctions in the quantity of refuse required relative to the results presented in Figures 21-24.

A study of the figures illustrates that the lowest net sludge disposal cost, based on refuse revenues of $16.50/Mg ($15/ton), occurs at the lower ratio of sludge to refuse (0.05). This results because at the low ratio the PUROX facility economics are determined by the refuse disposal fee. For refuse disposal fees of approximately $16.50/Mg ($15/ton), disposal of small quantities of sludge will be attractive. The refuse disposal fee is specific to the location and may be more or less than $16.50/Mg ($15/ton). Lower refuse disposal fees, such as those figures provided on the basis of $5.50/Mg or $5/ton of refuse, result in higher sludge to refuse ratios (0.60 case) becoming relatively more favorable.

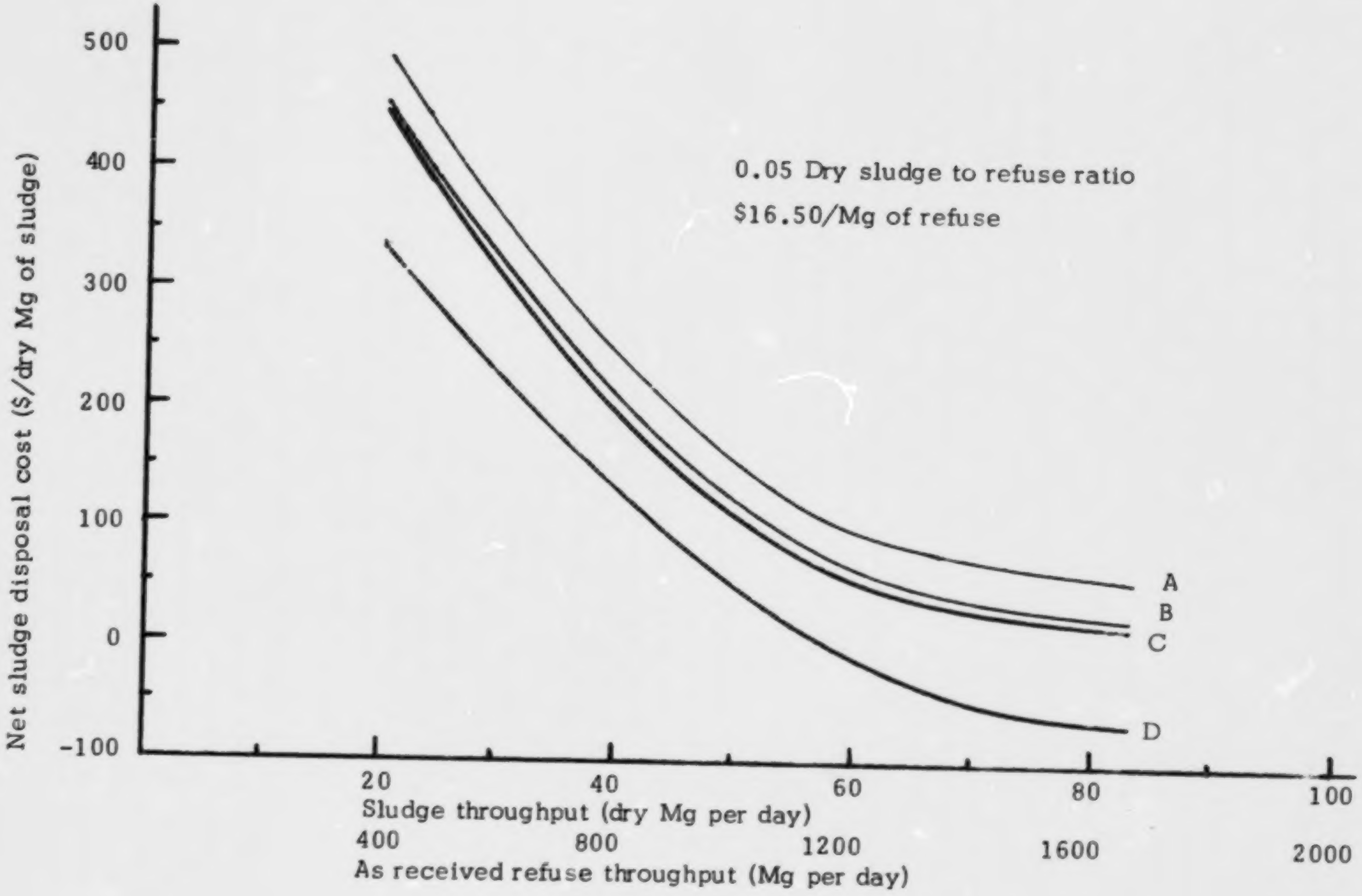

Figure 21. Estimated net sludge disposal cost.

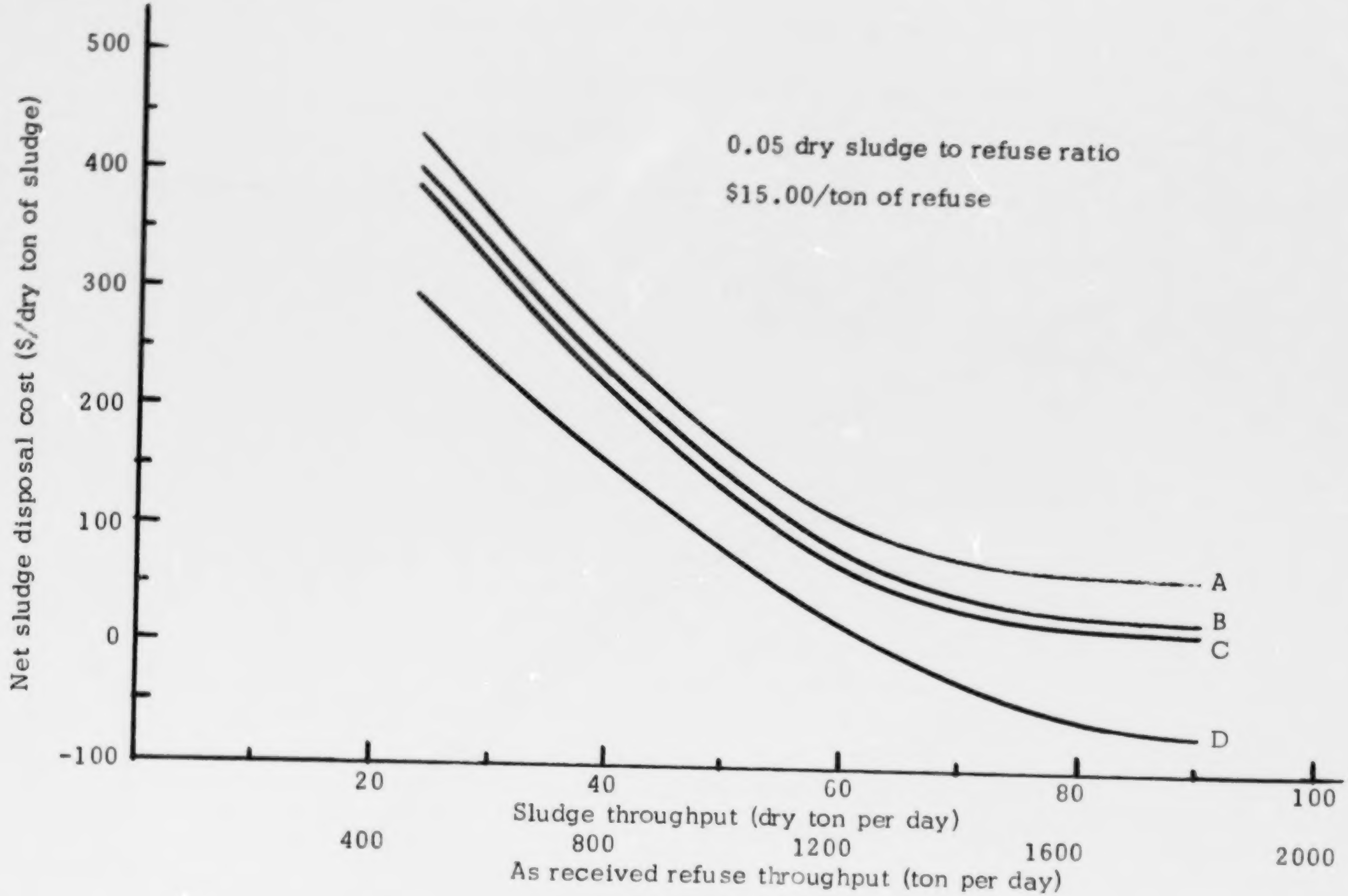

Figure 22. Estimated net sludge disposal cost.

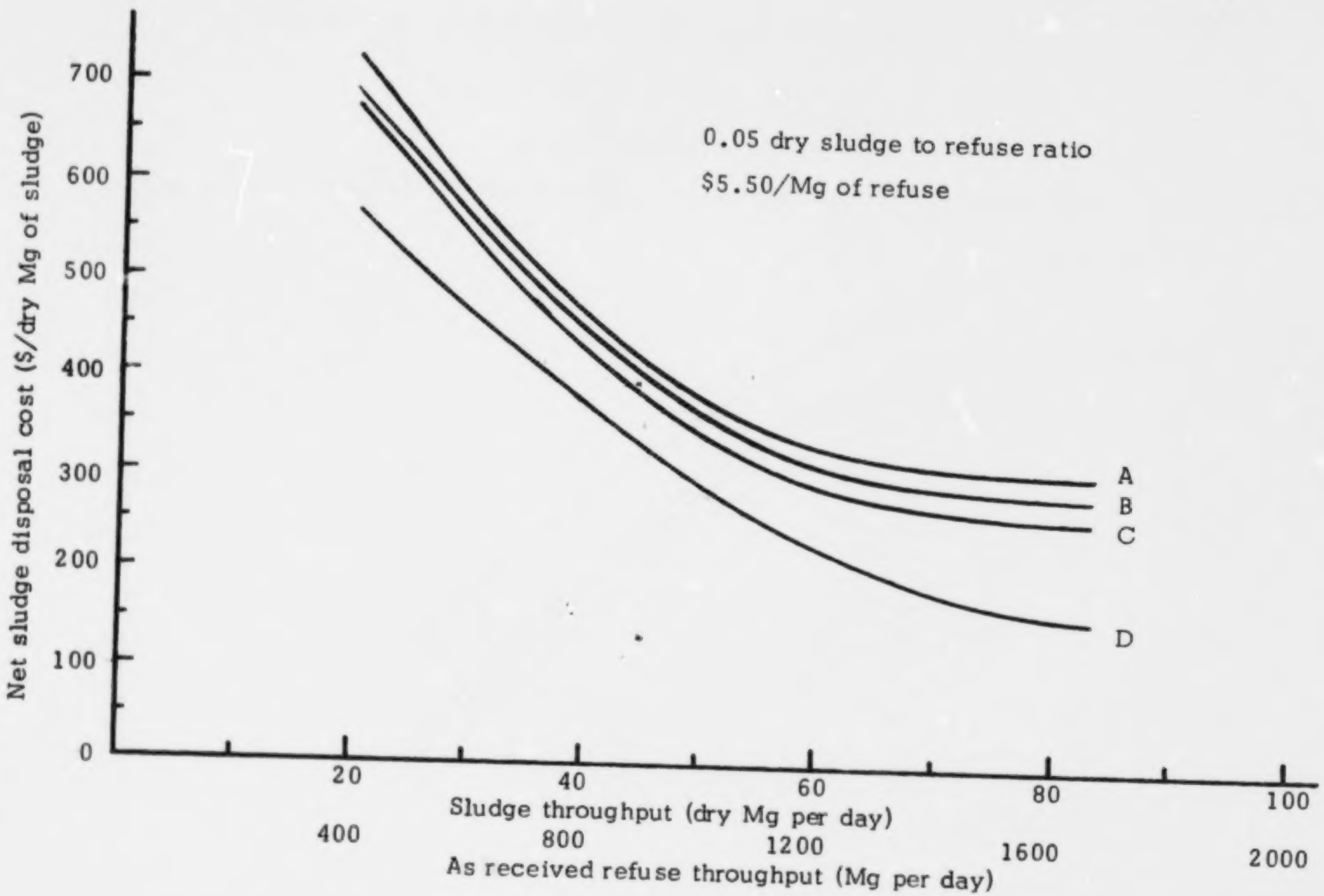

Figure 23. Estimated net sludge disposal cost.

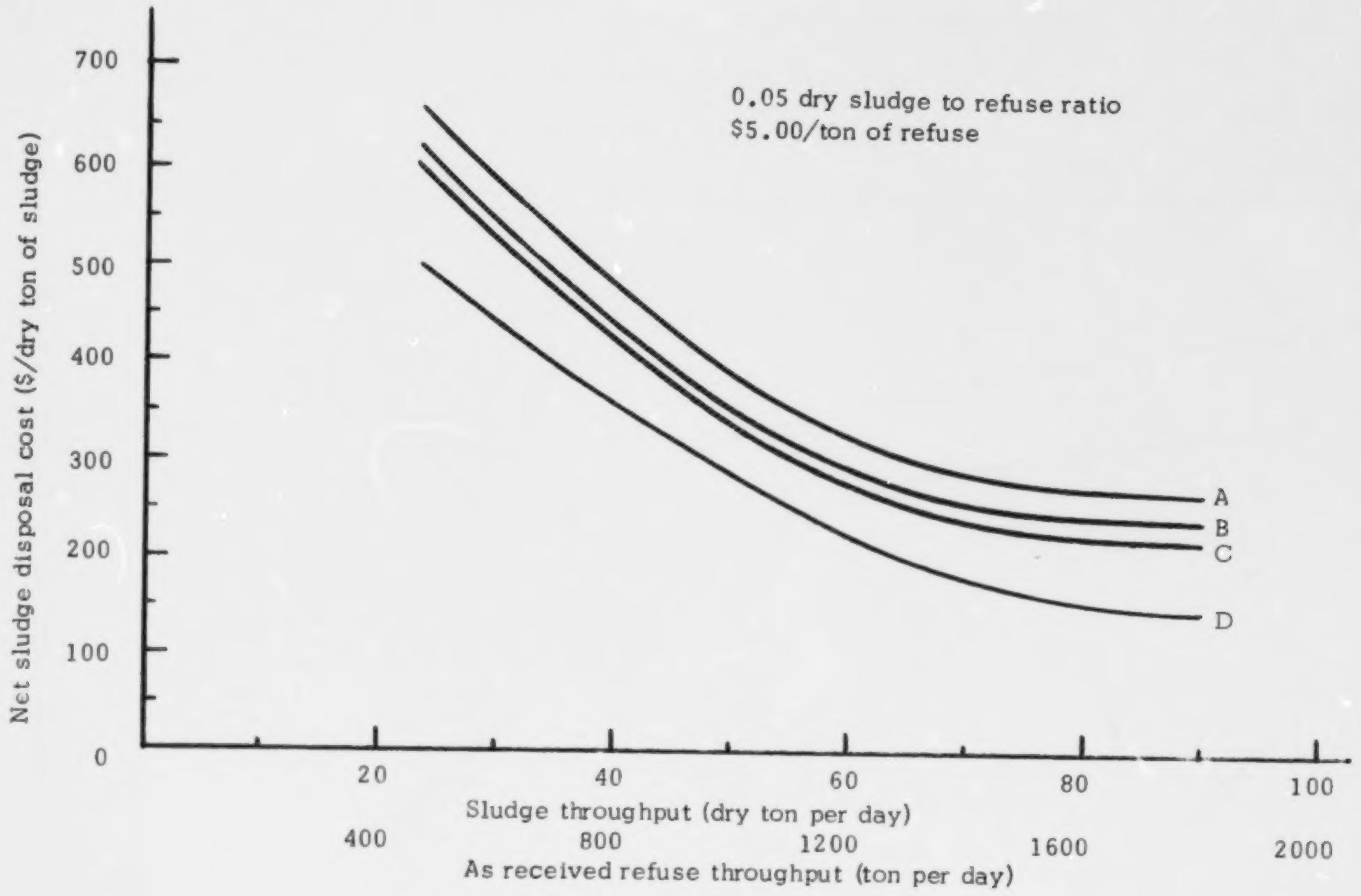

Figure 24. Estimated net sludge disposal cost.

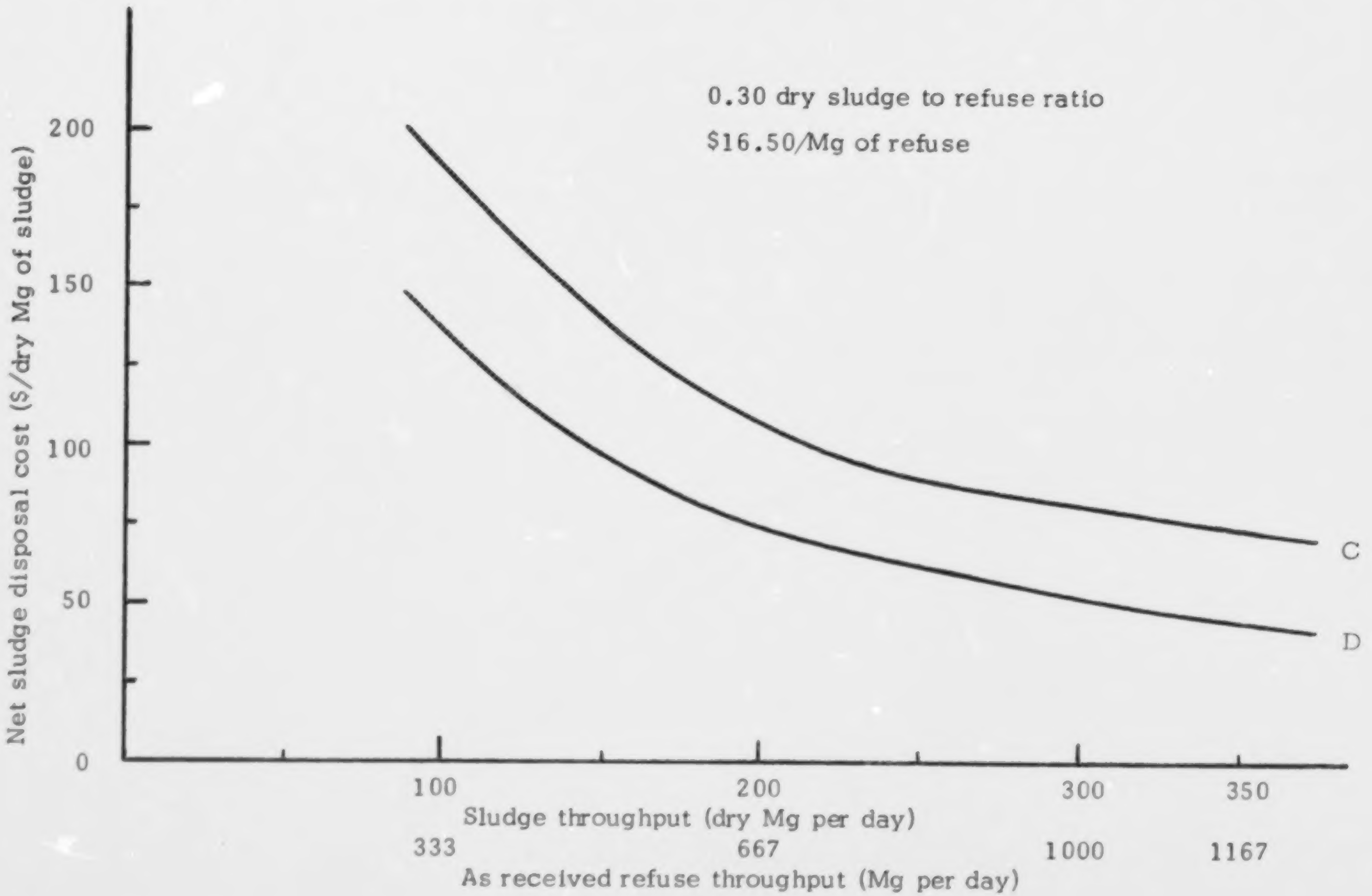

Figure 25. Estimated net sludge disposal cost.

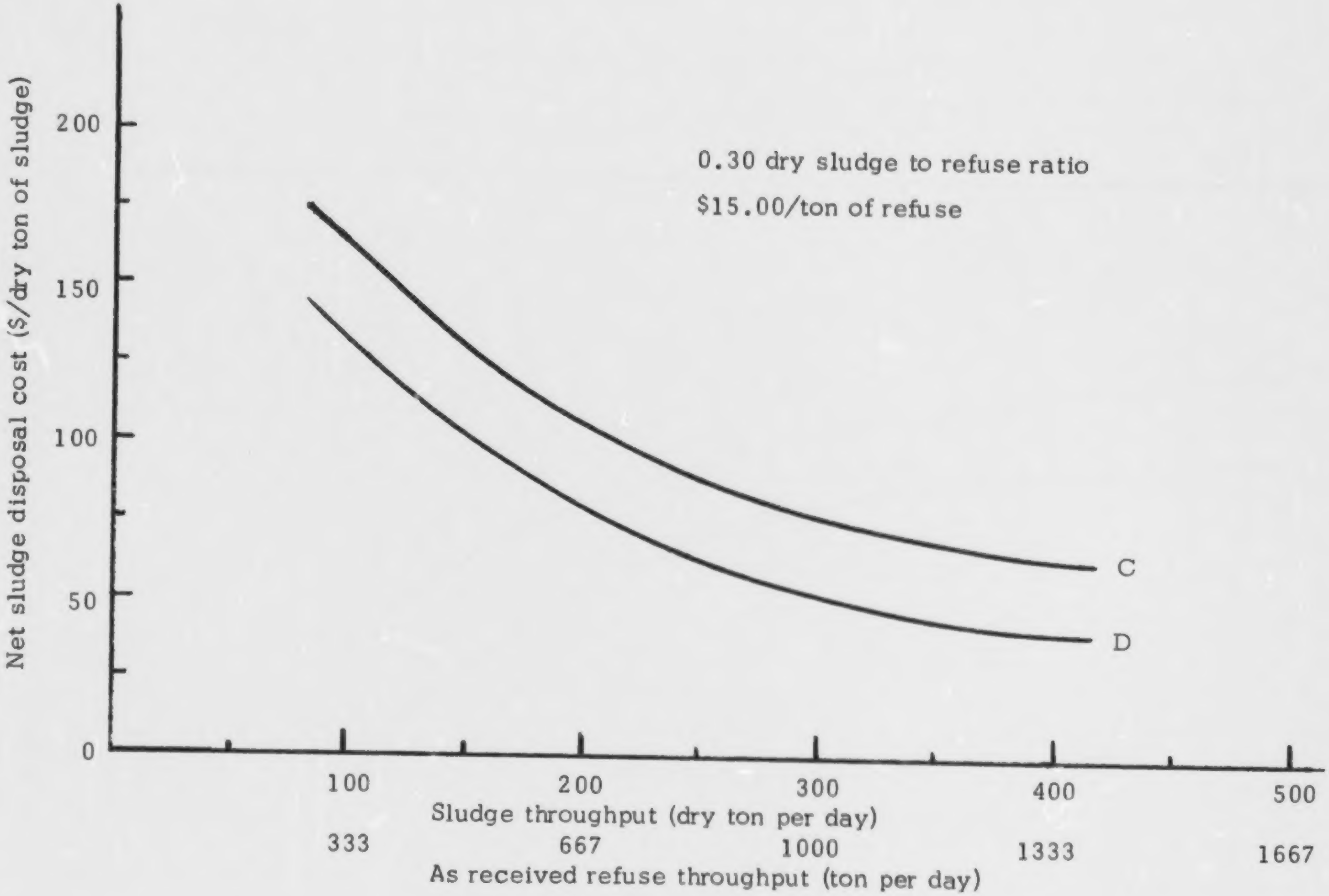

Figure 26. Estimated net sludge disposal cost.

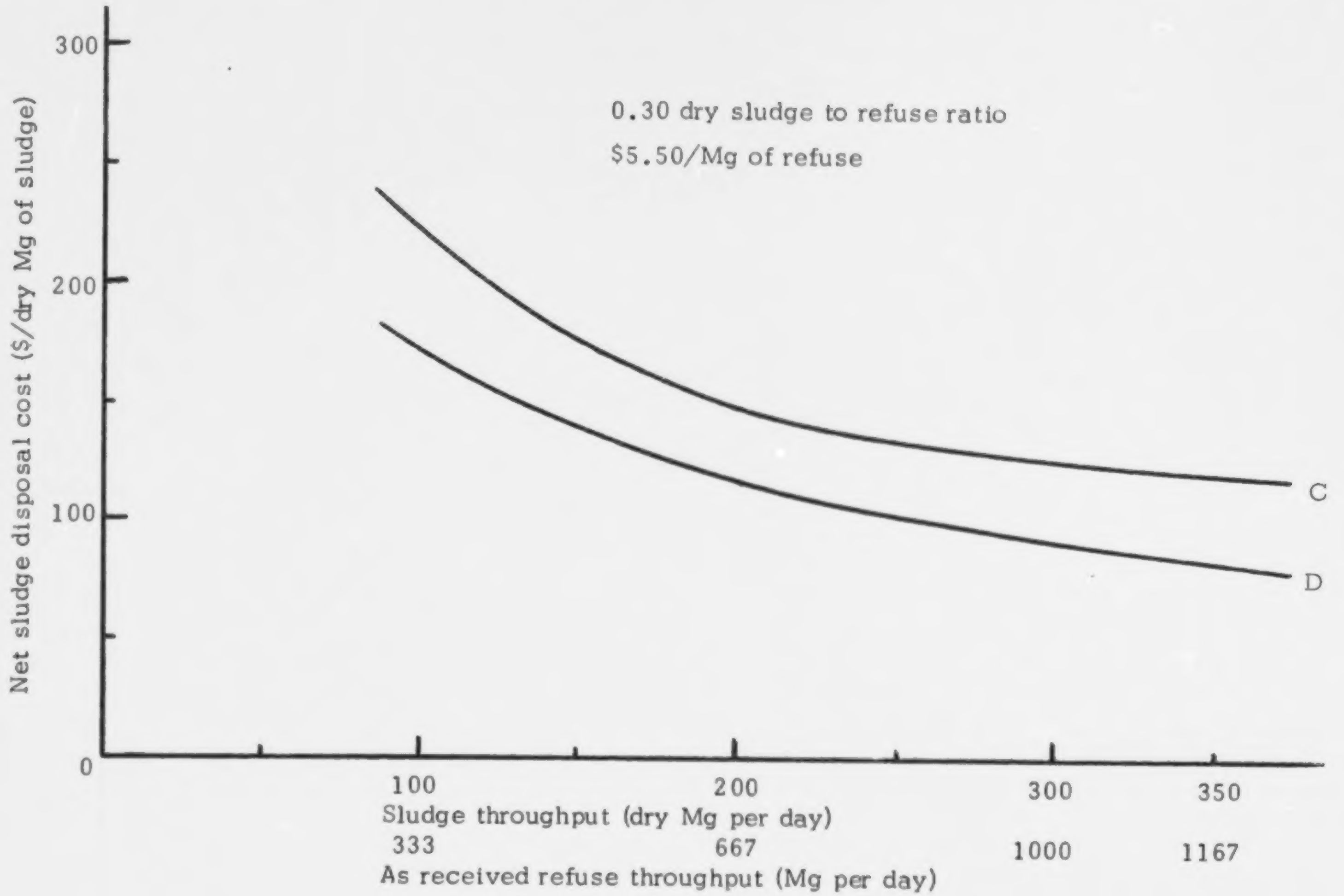

Figure 27. Estimated net sludge disposal cost.

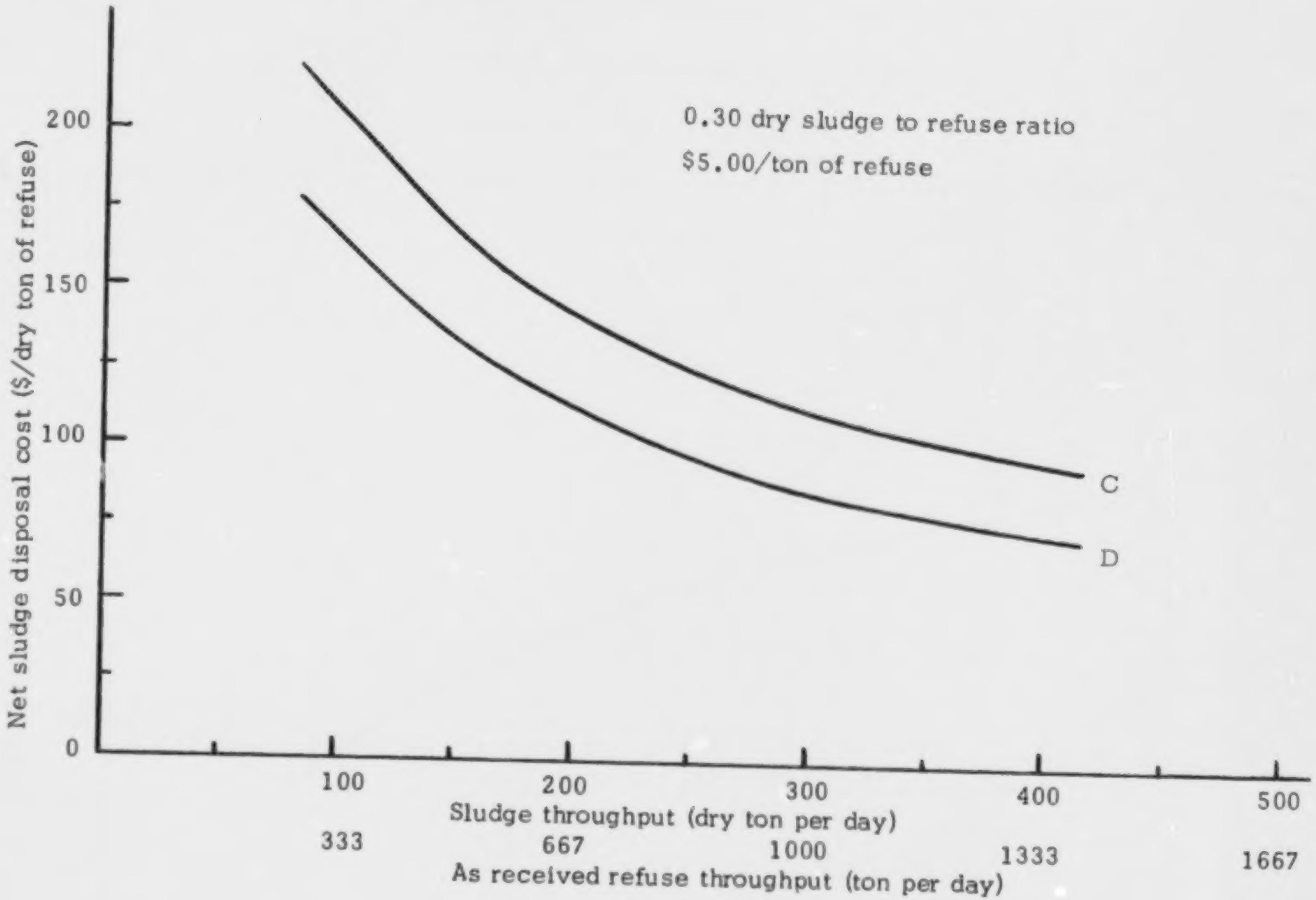

Figure 28. Estimated net sludge disposal cost.

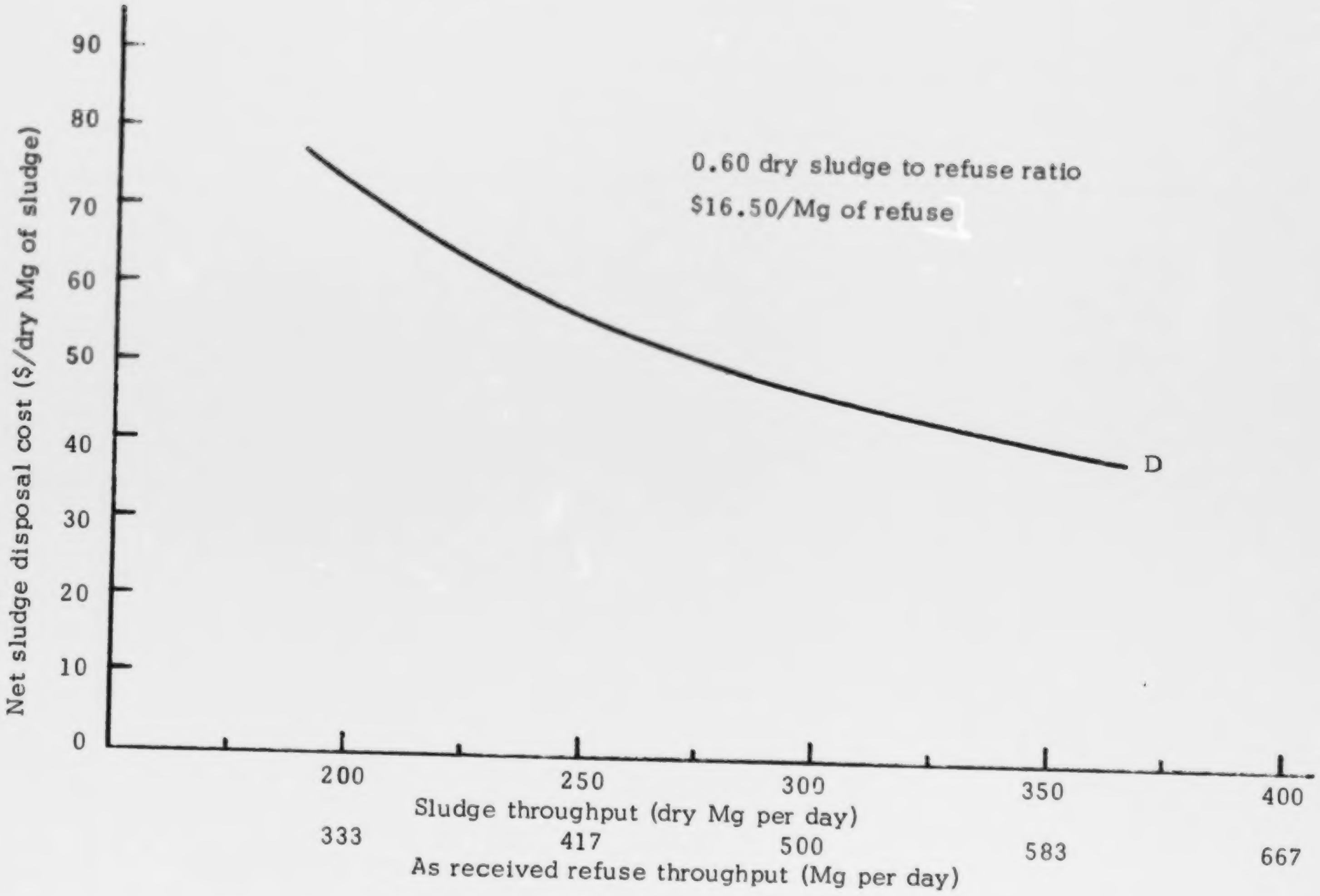

Figure 29. Estimated net sludge disposal cost.

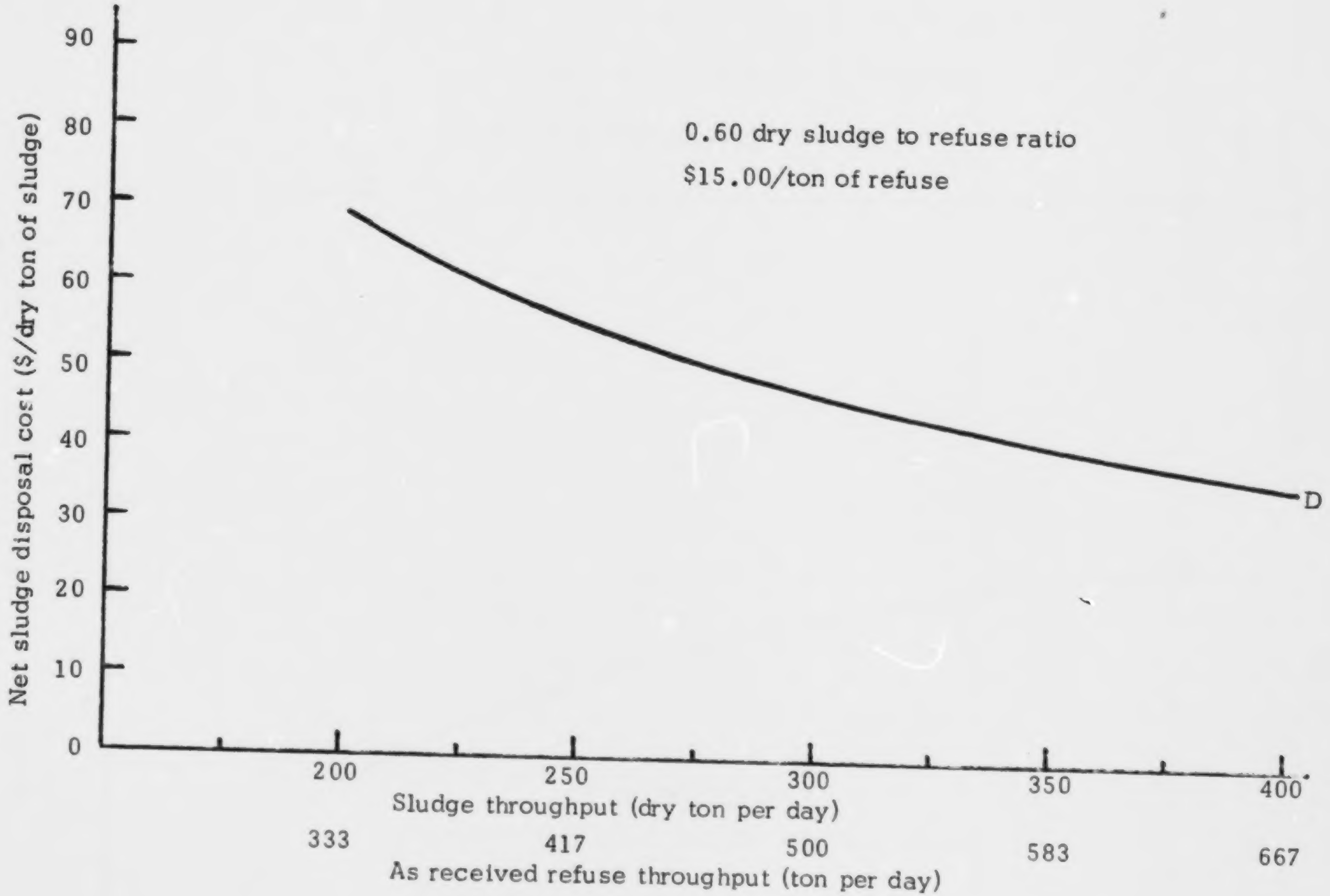

Figure 30. Estimated net sludge disposal cost.

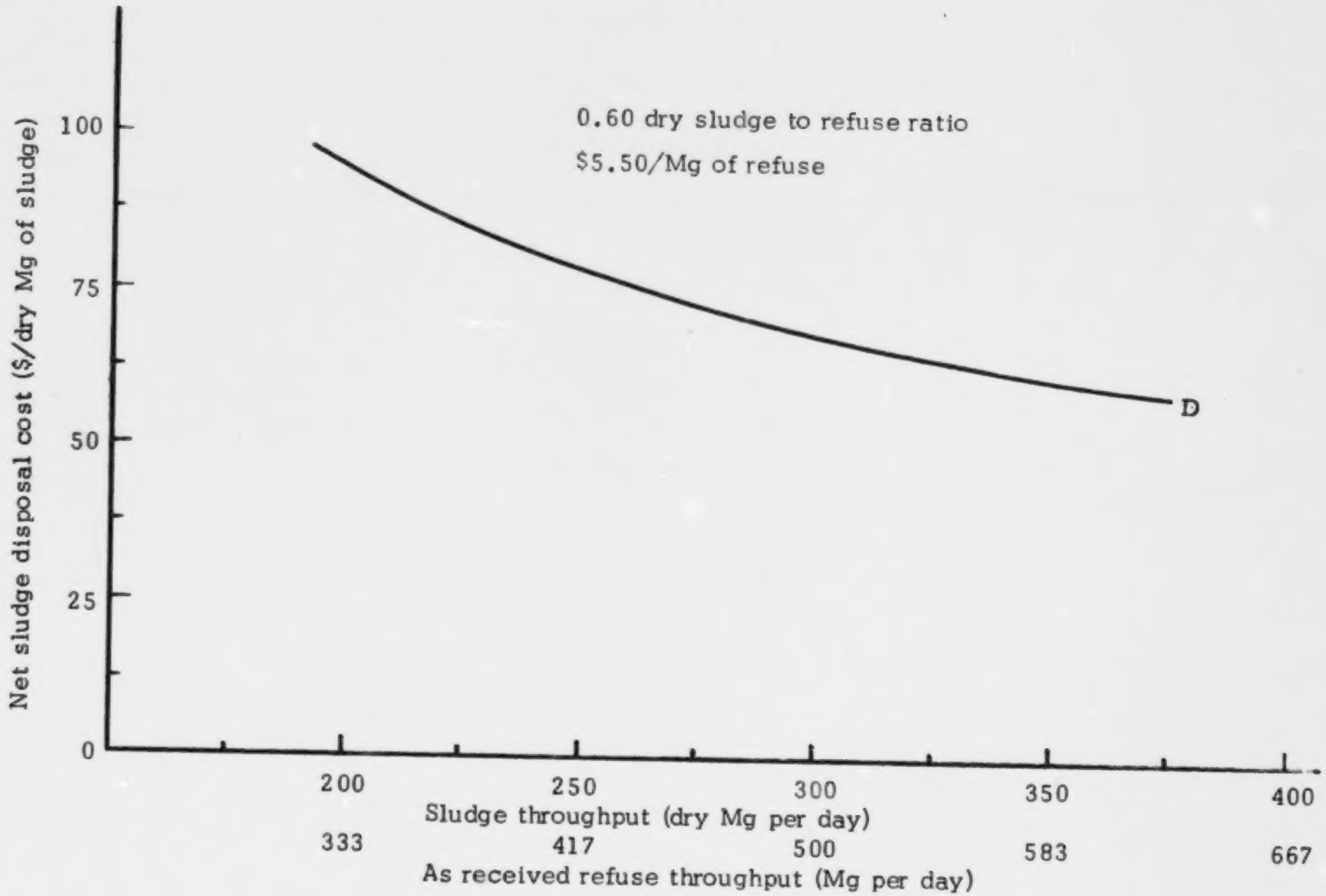

Figure 31. Estimated net sludge disposal cost.

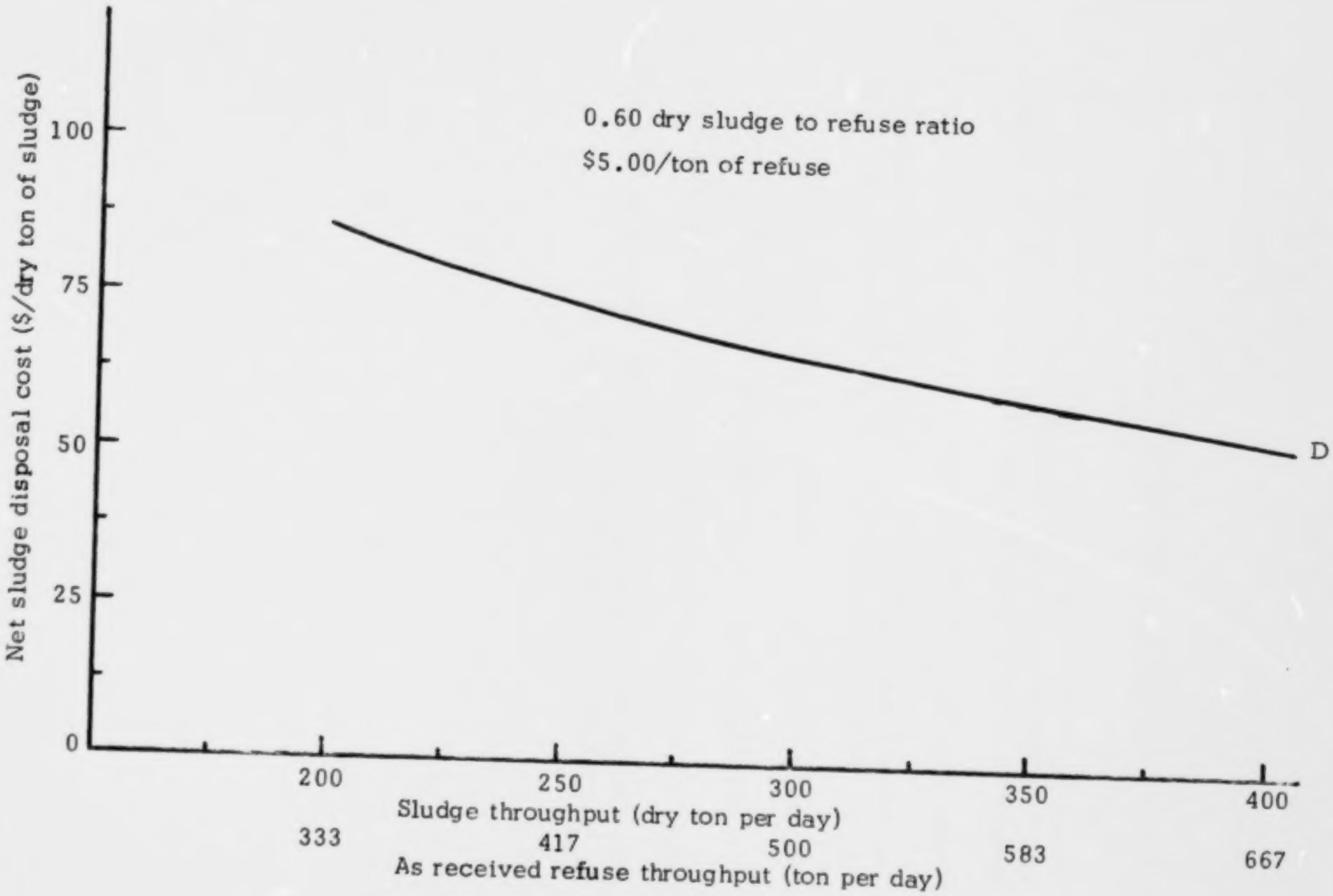

Figure 32. Estimated net sludge disposal cost.

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3. "Background Information for New Source Performance Standards", Vol. 3, EPA Report 450/2-74-003, APTD-13526, February, 1974.

4. Federal Register, Vol. 40, No. 248, December 24, 1975.

5. National Safety News, pp. 83-93, September, 1977.

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7. "A Guide to the Solution of Cost Effective Wastewater Treatment Systems," EPA Report 430/9-75-002, July, 1975.

APPENDIX A

ANALYTICAL PROCEDURES

All streams crossing the system boundaries were sampled. In general, a number of samples of each stream were taken during each run (typically, one week), and these were then composited for analysis. The streams sampled are listed below, and each is described in more detail later.

- Refuse
- Sludge
- Slag
- Wastewater
- Product gas
- Char
- Particulates from isokinetic samples
- Slag Leachate

REFUSE

Refuse analyses were subcontracted to Standard Laboratories of Charleston, WV. Ultimate and proximate analyses, as well as determinations of heating value, were performed on each composite. These were done in accordance with ASTM methods D3176-74, D3172-73 and D3286-73. Trace elements (see listing in Table A-1) were determined (generally) by atomic absorption.

SLUDGE

Sludge analyses were also subcontracted to Standard Laboratories. Again, ultimate, proximate, heating value, and trace element analyses were performed. Standard methods as noted above were used.

SLAG

Slag analyses were performed at the Union Carbide Corporation Contract Scientific Laboratory in Tarrytown, NY.

Majors were determined by X-ray fluorescence. The samples were ground to a fine powder, then fused in a Pt/Au crucible in a lanthanum oxide/lithium tetraborate matrix. This was then poured into a crucible mold. A polished disc was made, and the analysis was then performed.

TABLE A-1. DETECTION LIMITS FOR TRACE ELEMENTS

Constituent	Typical Detection Limits, ppm S. Charleston Lab	 Tarrytown
Zn	1.0	0.03
Cu	0.1	0.04
Cd	1.0	0.02
Ni	0.1	0.04
Fe	0.1	0.04
Hg	0.05	0.003*
Pb	0.1	0.05
Cr	0.1	0.04
Mn	0.1	0.02
Cl	1	0.01
F	-	0.05
P	1.0	0.1
As	0.1	0.1
Be	1.0	0.03
Ba	1.0	0.03
Se	-	0.05
Ag	0.1	0.03

*Lower limits can be attained if necessary.

Trace metals were determined by induction coupled plasma (ICP). The samples were dissolved in HF/HCl in a Teflon bomb @ 240 degrees C. The resulting solution was diluted with water, then aspirated into the sample chamber. The plasma is formed in argon carrier gas. (ICP is similar to emission spectroscopy, except that liquid samples can be analyzed. Also, since sample is energized in a plasma, no electrodes are required.)

Carbon samples were burned in O_2 at 1500 degrees C in induction furnace using an iron accelerator. CO_2 is captured on a molecular sieve. When combustion is complete, the molecular sieve is heated very rapidly, and the CO_2 is analyzed using a thermal conductivity sensor.

Sulfur usually determined by burning sample in induction furnace with iron accelerator at 1500 degrees C. The SO_2/SO_3 produced is absorbed in a KI/starch solution, then titrated with potassium iodate.

Chlorine, fluorine samples were ground, then pyrohydrolyzed at 1000 degrees C with steam, using vanadium oxide catalyst. The HF/HCl formed were distilled over, trapped in a water solution, and continuously titrated with NaOH. At the NaOH end point, aliquots were taken. Chlorine was determined by titrating potentiometrically with silver. Fluorine was determined by buffering the solution, then using an ion-selective electrode.

Mercury samples are prepared by grinding to a fine powder, then digesting in a Teflon bomb at 150 degrees C with $HF/H_2SO_4/KMnO_4$ solution. The permanganate is reduced with hydroxylamine hydrochloride ($NH_2OH \cdot HCl$), then the sample is placed in the sample holder of the atomic absorption unit and reduced in situ with stannous chloride. The measurement is made via a cold vapor technique.

WASTEWATER

Wastewater was normally analyzed by personnel at the Union Carbide Chemicals and Plastics facility in South Charleston. Certain samples were run independently at the Central Scientific Lab in Tarrytown.

Grease and oil were separated by extraction, then determined gravimetrically. Suspended solids (weight) determined by filtering sample, then weighing. COD is determined by refluxing sample with dichromate/ sulfuric acid solution. Mercury/silver salt complex is added during digestion to catalyze the reaction. Excess dichromate is titrated with ferrous ammonium sulfate. BOD determination is a complex procedure. Complete description may be found in the latest edition of APHA "Standard Methods for Examination of Water and Wastewater". Essentially, the procedure calls for seeding the sample with microorganisms and incubating for five days. Residual dissolved oxygen can then be determined, normally by using the azide modification of the iodometric method. TOC is determined by instrumental means. The carbon is burned in an oxygen stream, and the resulting CO_2 is then measured. Mercury is determined in the same fashion as previously described, except that the sample preparation steps are not necessary. Chlorine and fluorine are determined by argentometric titration and ion-selective electrode, respectively. pH is measured with a pH meter. Trace metals measured directly with ICP.

Suspended Solids

For trace metals samples were dried at 105 degrees C, dissolved using the Teflon bomb technique, then the solution was run by ICP. Mercury and sulfur were analyzed using the techniques described previously.

For C, H, N the samples are mixed with a catalyst and burned at 1000 degrees C. The gas, containing H_2O, CO_2 and NO_x is passed through a tube containing Cu metal at 600 degrees C to convert NO_x to N_2. The gas then goes into a gas chromatography column, and the components are analyzed via a thermal conductivity detector.

PRODUCT GAS

Gas samples were not composited. Normally, several samples were collected twice per day. Helium was metered into the gas upstream of the sample point, prior to collection of each gas sample, to provide a method of estimating the gas volumetric flow. The samples were analyzed by mass spectrometer. Typically, all compounds in concentrations greater than 0.001 volume % were reported - this usually included up to about 35-40 compounds. Analyses of O_2 and natural gas were also done by mass spectrometer to establish baseline conditions.

CHAR

Char analyses were subcontracted to Standard Laboratories. Analyses were the same as those for refuse and for sludge.

PARTICULATES

Environmental Protection Agency Method 5 was used to collect the product gas. The isokinetic technique was used to calculate the gas volumetric flow rate, and to collect particulates to determine grain loading in the gas. The total particulate catch was typically quite small, reflecting very low grain loading in the gas.

Trace metals were determined by dissolving the sample in HCl/HNO_3. (If organics did not decompose, perchloric acid was added.) The solution was then run by ICP. Where sample size permitted, mercury, sulfur carbon, hydrogen and nitrogen analyses were run.

SLAG LEACHATE

To ascertain whether PUROX slag is inert, samples of slag were agitated with distilled water for up to two weeks. Analyses were similar to those for the wastewater samples.

A list of analytical instruments that were used is given in Table A-2.

TABLE A-2. ANALYTICAL INSTRUMENTS

X-Ray Fluorescence	A Siemens SRS-1 sequential X-Ray fluorescence spectrometer, with Siemens K-4 X-ray generator, chromium X-ray tube, and PDP-11 minicomputer was utilized.
Atomic Absorption	A Perkin Elmer 460 atomic absorption spectrophotometer was used.
Carbon/Hydrogen/ Nigrogen Analyzer	An F & M Scientific #185 (Hewlett-Packard) C-H-N analyzer (uses He carrier gas, oxygen generated catalytically) was employed.
Carbon Analyzer	LECO induction furnace and Angstrom Carbomatic #523C (uses O_2 for combustion and as carrier gas) was used.
Sulfur Analyzer	LECO induction furnace #521S was used.
Pyrohydrolysis Unit	Nickel tube in Lindberg Hevi-Duty Furnace #2000 was used to carry out the following analyses: Fluorine analysis - Orion ion-selective electrode in pH meter. Chlorine - Orion silver sulfide electrode in pH meter.
Induction Coupled Plasma	Jarrell Ash Cat. No. 90975 (specially modified by J. A. for Tarrytown Laboratory) was used.

APPENDIX B

TEST PERIOD 5. REFUSE ONLY - 25 MAY - 1 JUNE 1977

During the period between 25 May and 1 June the PUROX System was operated on refuse only to provide a baseline for comparison with sludge processing. An overall material balance was calculated for the refuse only baseline period to provide a reference for the sludge processing results. The balance is shown in Table B-1. The slag and metal streams were determined using the methods described in Section 8. The dry, inert free, gas flow rate was calculated using the helium trace data. Argon was added to the gas flow rate based on the average gas composition determined for the period. Nitrogen equal to the mass of nitrogen in the oxygen supply was also added to the product gas. The gas stream was then saturated with water at 21 degrees C (70 degrees F). The sum of dry gas, nitrogen, argon, and water masses was the total gas flow rate. The dry char production rate was correlated with the converter operating rate to obtain a functional relationship between char production rate and operating rate. Because the oil stream was not measured it was assumed to be 2 percent by weight of the incoming refuse based on previous measurements.

The water stream was calculated by difference between the entering and exiting masses. As a check the effluent production in gallons per ton of refuse processed was calculated and compared to previous balances performed on the system. The calculated result was 0.346 cubic meter per Mg (83 gallons per ton) which compared well with previous measurements which fell between 0.334 and 0.417 cubic meters per Mg (80 and 100 gallons per ton).

Gas production during this period was 437.1 Nm^3 (normal cubic meters, 0 degrees C, 101 KPa) [14,800 Sft^3 (standard cubic feet, 60 degrees F, one atmosphere)] of dry, inert free gas per Mg (ton) of refuse and fuel gas consumed. The ratio is the mean of six samples which ranged between 410.5 and 466.6 Nm^3 per Mg [13,900 and 15,800 Sft^3/ton]. The pitot tube result was 325.6 Nm^3/ Mg (11,026 Sft^3 per ton) of feed. Significant error is possible in the calculated average gas flow rate. The standard deviation of 12 pitot tube measurements taken over a two hour period on 26 May was 97 Nm^3/Mg (3285 Sft^3 per ton).

TABLE B-1. PUROX SYSTEM MASS BALANCE, TEST PERIOD 5 (Metric)

Basis: 1 Day

Stream	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse							
(as received)	73.5	-	-	-	-	-	-
(as fed)	-	16.5	1.9	10.9	0.1	21.9	15.7
Sludge	-	-	-	-	-	-	-
Fuel Gas	1.7	1.4	0.3	-	-	-	-
Oxygen	15.1	-	-	14.7	-	-	-
Total In	90.3	-	-	-	-	-	-
Metal	6.2	-	-	-	-	-	-
PUROX Gas	37.9	14.6	1.6	20.4	-	0.7	-
Slag	16.8	0.3	-	1.8	-	-	14.7
Char	2.5	1.4	0.1	-	1.0	-	1.0
Oil	1.5	1.1	0.2	0.2	-	-	-
Wastewater	25.4	0.5	0.1	0.6	0.1	24.1	-
Total Out	90.3	-	-	-	-	-	-

TABLE B-2. PUROX SYSTEM MASS BALANCE, TEST PERIOD 5 (English)

Basis: 1 Day

Stream	Total (Tons)	C (Tons)	H (Tons)	O (Tons)	S (Tons)	H_2O (Tons)	Ash (Tons)
Refuse (as received)	81.0	-	-	-	-	-	-
(as fed)	-	18.2	2.1	12.0	0.1	24.1	17.3
Fuel Gas	1.9	1.5	0.4	-	-	-	-
Oxygen	16.7	-	-	16.2	-	-	-
Total In	99.6	-	-	-	-	-	-
Metal	6.8	-	-	-	-	-	-
PUROX Gas	41.8	16.1	1.8	22.5	-	0.8	-
Slag	18.5	0.3	-	2.0	-	-	16.2
Char	2.8	1.6	0.1	-	-	-	1.1
Oil	1.6	1.2	0.2	0.2	-	-	-
Water	28.1	0.5	0.1	0.7	0.1	26.4	-
Total Out	99.6	-	-	-	-	-	-

The oxygen consumption was 0.201 Mg (tons) oxygen per Mg (tons) of refuse plus fuel gas. The consumption ratio includes fuel gas in the denominator because the ratio is a partial function of the fuel gas rate and because this method is consistent with previous studies. The ferrous metals separation ratio was 0.08 Mg (tons) of metal per Mg (ton) of refuse. This ratio is primarily dependent on the metals content of the incoming refuse. Slag production was 0.23 Mg (tons) of slag per Mg (ton) of refuse.

Component balances were performed on the system for major constituents, carbon, hydrogen, oxygen, sulfur, and water. A balance was also performed on the noncombustible portion of the incoming streams. This balance includes unseparated metal, glass, and ash; the component was named "ash". The assumptions for the component mass balance are given in Table B-3.

TABLE B-3. ASSUMPTIONS FOR COMPONENT MASS BALANCES

(1) Wastewater stream COD is approximately 50,000 ppm.

(2) Soluble organic compounds in the wastewater have the C:H:O ratio of acetic acid (CH_3COOH).

(3) Water produced by combustion and pyrolysis in the hearth is 0.042 m^3/Mg of feed (10 gal/ton).

(4) All SiO_2 in the slag entered as oxide. Other oxides present were oxidized from metal in hearth.

(5) The ESP oil has a composition of 80% carbon by weight, 10% hydrogen, and 10% oxygen.

Product gas composition and ultimate analysis were determined by averaging all gas samples obtained during the test period. The result is shown in Table B-4. The slag composition used was the sample result from this test period. The oxygen balance was calculated from the oxide concentration in the slag. Oxygen present in the slag as SiO_2 was assumed to have entered the process as glass and was included in the "ash" balance. The char composition was the average of three samples taken during the period. Oil was assumed to have the composition listed in Table B-3. The composition of the water stream was determined by difference.

TABLE B-4. AVERAGE PRODUCT GAS ANALYSIS

Test Period 5

	Mole Percent
H_2	28.14
CO	37.28
CH_4	6.21
C_2H_2	0.46
C_2H_4	1.90
C_2H_6	0.44
C_3H_6	0.32
C_3H_8	0.23
C_4	0.40
C_5	0.29
C_6H_6	0.24
HHC	0.26
H_2S	0.02
CH_3OH	0.11
CO_2	23.07
O_2	0.03
Ar	0.59

The first set of balances calculated used the average refuse composition determined from the three refuse samples analyzed. The mean composition was used because the three samples exhibited substantial variation in moisture, carbon, and ash content. The component balances obtained using the mean refuse analysis were unsatisfactory. The incoming ash was insufficient to account for the ash contained in the slag. The entering carbon was much more than the carbon contained in the product gas, char and oil. Assignment of all excess carbon to the effluent water resulted in a concentration which was inconsistent with previous experience and with the results of wastewater samples obtained. Similar results were obtained during all periods of sludge processing when the mean refuse analysis was used.

Because use of the refuse analyses obtained resulted in poor component balances a different method was chosen to calculate typical balances. Several assumptions were made which specified the effluent stream. The assumptions are listed in Table B-3. The composition of refuse necessary to balance the system was then calculated and compared to typical published refuse analyses. The component balances obtained using this technique are shown alongside the overall balance in Tables B-1 and B-2.

The hydrogen, oxygen, and water do not balance separately. This is due to the production of water in the pyrolysis and combustion reactions. The missing mass of hydrogen and oxygen can be found in the water column.

Balances were performed on 9 trace metals of particular interest. The assumptions used in these balances are given in Table B-5. Analyses were performed for several other trace components, but they were either below the sensitivity of the particular analysis or were not of special interest. The results are shown in Tables B-6 and B-7.

TABLE B-5. ASSUMPTIONS FOR TRACE METAL BALANCES

(1) Trace metal analyses are on a wet basis

(2) Char was 40% moisture by weight

(3) Scrubber flow was 0.38 m^3/min (100 gal/min)

(4) Condensation in the scrubber is 0.023 m^3/min (6 gal/min)

The incoming quantities of the metals were determined using the average concentration in the three refuse samples taken. Since the average refuse analysis was unrepresentative for major components it was probably also unrepresentative for trace elements. For this reason the balances are probably inaccurate, and the distribution of the trace metal between slag, char and water are of greater significance. The amount of trace metals in the slag and wastewater exit streams were calculated from the analysis of samples taken during this test period. Unfortunately the dilution of the wastewater by makeup water to the scrubber makes the metals content of the wastewater stream uncertain. Char metals content was based on the average of three samples obtained.

Due to dilution effects the concentrations of cadmium and mercury in the effluent water were below the detection limits for their respective analyses. Since significant quantities of metal could be contained in these streams below the detection limit, no conclusion can be drawn from this test concerning the ultimate distribution of these two metals. The char stream contained a large fraction of the exiting amounts of lead and zinc. The distribution of these two metals between the exit streams under particulate recycle conditions was not known, but for both these metals the amount in the slag is several times the amount in the wastewater. For the remaining five metals, chromium, copper, iron, manganese, and nickel the majority of the metal exited in the slag. The portion of each metal in the exiting streams is shown for comparison purposes.

The heat balance shown in Table B-8 was performed on the system to evaluate the efficiency of energy conversion. Because of refuse heating value uncertainty the calculated efficiency was based on the total heat contained in the exit streams. The assumptions made in calculating the heat balance are listed in Table 11. Heating values are expressed as higher heating value and sensible heats are referenced to 15 degrees C (60 degrees F). The projection to the case of total particulate recycle is discussed in detail in Section 11.

The measured refuse heating value excluding metal oxidation used was 18.2 MJ per kg (7831 Btu per pound) on a dry basis and was the average of three samples. A small change in this value produces a substantial effect in the heat balance. Product gas heating values were calculated for each sample from the composition of the gas determined by sampling. The value used in the heat balance was the average of all gas samples obtained during the test period. Char heating value was the average of the values from samples. Oil and water stream heating values were assumed based on previous PUROX System tests (see Table 11).

The heat lost was composed of three large losses: hearth cooling loss, converter convective and radiation loss, and condenser cooling loss. The hearth cooling loss was measured from temperature changes in the cooling water and its rate and the value determined was applied to all test periods. This was a good assumption since hearth temperatures were relatively constant for all operating conditions. The converter convective and radiation loss was calculated in previous studies and this value was applied to all test periods also. The condenser loss was estimated by taking the water stream from nominal converter exit conditions of 260 degrees C (500 degrees F) to condenser outlet conditions of 21 degrees C (70 degrees F).

Based on the exit streams the efficiency of energy conversion was 63.6 percent. Under conditions of char recycle an efficiency of 77 percent would be expected based on the analysis in Section 11.

TABLE B-6. TRACE METAL BALANCE, TEST PERIOD 5 (Metric)

Basis: 1 Day

Metal	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	0.86	16.6	23.4	388.8	11.8	51.8	4.7	153.0	1.81
Sludge	-	-	-	-	-	-	-	-	-
Total In	0.86	16.6	23.4	388.8	11.8	51.8	4.7	153.0	1.81
Slag	0.09	57.1	67.1	1040.5	1.6	26.9	5.1	5.2	0.50
Char	0.23	2.4	6.5	71.3	25.0	2.4	0.2	82.7	0.00
Wastewater*	<0.59	0.1	0.1	38.1	0.1	0.6	0.1	2.5	<27.2
Total Out	0.31	59.6	73.7	1149.9	26.7	29.9	5.4	90.4	0.50
Percent of Total Out									
Slag	25.8	95.8	91.0	90.5	6.0	90.0	94.4	5.8	100.0
Char	74.2	4.0	8.8	6.2	93.6	8.0	3.7	91.5	-
Wastewater	-	0.2	0.2	3.3	0.4	2.0	1.9	2.7	-

*Quantities for Cd and Hg are based on detection limits.

TABLE B-7. TRACE METAL BALANCE, TEST PERIOD 5 (English)

Basis: 1 Day

Metal	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	1.9	36.7	51.6	857.2	26.0	114.1	10.3	337.2	3.99
Sludge	-	-	-	-	-	-	-	-	-
Total In	1.9	36.7	51.6	857.2	26.0	114.1	10.3	337.2	3.99
Slag	.19	125.8	148.0	2294.0	3.5	59.2	11.3	11.4	1.11
Char	0.5	5.2	14.3	157.2	55.2	5.2	0.5	182.3	0.01
Wastewater *	<1.3	0.13	0.1	84.0	0.13	1.3	0.2	5.6	< 60
Total Out	0.69	131.0	162.4	2535.2	58.7	65.7	12.0	199.3	1.12
Percent of Total Out									
Slag	25.8	95.8	91.0	90.5	6.0	90.0	94.4	5.8	100
Char	74.2	4.0	8.8	6.2	93.6	8.0	3.7	91.5	-
Wastewater	-	0.2	0.2	3.3	0.4	2.0	1.9	2.7	-

* Quantities of Cd and Hg are based on detection limits.

TABLE B-8. PUROX SYSTEM HEAT BALANCE, TEST PERIOD 5

	GJ/Day	Btu x 10^{-6}/Day
Refuse*	827.9	784.7
Sludge	-	-
Fuel Gas	92.7	87.9
Oxygen	-	-
Total In	920.6	872.6
Metal	-	-
Gas	507.6	481.1
Slag	33.2	31.5
Char	55.3	52.4
Oil	57.4	54.4
Wastewater	38.4	36.4
Losses	105.6	100.1
Total Out	797.5	755.9
	123.1	116.7
Efficiency (as operated)	63.6 Percent	
Of Conversion (as projected)	77.0 Percent	

*Value is average for entire program. Efficiency based on total out.

APPENDIX C

TEST PERIOD 1. PRIMARY SLUDGE - April 19-25, 1977

The plant processed its first sludge during the period of 19 to 25 April 1977. Feeding of 32.4 percent solid dewatered primary sludge cake from Huntington, West Virginia, began at 2200 on 19 April 1977 at an approximate operating rate of 77.1 Mg (85 tons) per day of refuse and 6.2 Mg (5.6 tons) per day of sludge. The dry sludge-to-refuse ratio was 0.02. Operation was smooth for two days though several minor problems occurred. The plant was automatically shut down at 1055 on 21 April when an electrician accidentally shorted the shutdown circuit while wiring the ESP recycle blower. A rapid startup was conducted and the plant was operating by 1230. The vacuum filter was tested on 22 April and operated for 3.5 hours on 23 April. The scrubber was operated on recycle water during this time. Several troublesome problems occured in the front end between 22 and 24 April but rate was only affected once until shredder problems precluded feeding during the morning of 25 April. The test period was ended when the shredder drive sheaves failed and the plant was shut down.

The heat and mass balances calculated for the first sludge test period are shown in Tables C-1 through C-6. Sludge was fed to the converter as 6 percent of the feed stream on a wet basis. The balances were obtained by the methods described in Appendix B. Similar problems to those which occurred during calculation of the refuse only balance were encountered with these balances.

TABLE C-1 MASS AND COMPONENT BALANCE, TEST PERIOD 1

Basis: 1 Day

STREAM	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse (as received)	77.1	-	-	-	-	-	-
(as fed)	-	16.9	2.1	13.4	0.2	21.8	18.1
Sludge	5.1	0.5	0.1	0.2	-	3.4	0.8
Fuel Gas	1.3	1.0	0.3	-	-	-	-
Oxygen	14.1	-	-	13.6	-	-	-
Total In	97.6	-	-	-	-	-	-
Metal	4.2	-	-	-	-	-	-
PUROX Gas	38.7	14.5	1.7	21.2	-	0.7	-
Slag	19.9	0.2	-	2.2	-	19.5	17.5
Char	3.4	1.9	0.1	-	0.1	1.3	1.4
Oil	1.6	1.3	0.2	0.2	-	-	-
Wastewater	29.8	0.5	0.1	0.8	0.1	28.3	-
Total Out	97.6	-	-	-	-	-	-

TABLE C-2 MASS AND COMPONENT BALANCE, TEST PERIOD 1 (English)

Basis: 1 Day

Component Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse (as received)	85.0	-	-	-	-	-	-
(as fed)	-	18.6	2.3	14.8	0.2	24.0	19.9
Sludge	5.6	0.6	0.1	0.2	0.0	3.8	0.9
Fuel Gas	1.4	1.1	0.3	-	-	-	-
Oxygen	15.5	-	-	15.0	-	-	-
Total In	107.5	-	-	-	-	-	-
Metal	4.6	-	-	-	-	-	-
PUROX Gas	42.7	16.0	1.9	23.4	-	0.8	-
Slag	21.9	0.2	-	2.4	0.0	-	19.3
Char	3.8	2.1	0.1	0.0	0.1	-	1.5
Oil	1.8	1.4	0.2	0.2	-	-	-
Wastewater	32.7	0.6	0.1	0.8	0.1	30.6	-
Heat Losses	-	-	-	-	-	-	-
Total Out	107.5	-	-	-	-	-	-

TABLE C-3 AVERAGE PRODUCT GAS ANALYSIS, TEST PERIOD 1

	Mole Percent
H_2	31.25
CO	36.24
CH_4	4.46
C_2H_2	0.25
C_2H_4	1.32
C_2H_6	0.33
C_3H_6	0.27
C_3H_8	0.25
C_4	0.47
C_5	0.35
C_6H_6	0.17
HHC	0.32
H_2S	0.00
CH_3OH	0.14
CO_2	23.52
O_2	0.05
Ar	0.62

TABLE C-4 TRACE METAL BALANCE, TEST PERIOD 1 (Metric)

Basis: 1 Day

Metal Stream	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	0.91	18.0	25.4	421.3	12.8	56.1	5.0	165.7	1.96
Sludge	0.18	10.5	27.3	308.3	1.5	4.1	93.5	5.8	-
Total In	1.09	28.5	52.7	729.6	14.3	60.2	98.5	171.5	1.96
Slag	0.18	17.7	85.4	1092.7	2.4	23.9	53.7	9.0	0.20
Char	0.32	2.2	10.2	105.4	30.3	3.6	10.3	141.5	0.01
Wastewater*	-	-	-	-	-	-	-	-	-
Total Out	0.40	19.9	95.6	1198.1	32.7	27.5	64.0	150.5	0.21

* No water sample taken during this period

Percent of Total Out

Slag	36.4	88.9	89.3	91.2	7.3	86.9	83.9	6.0	95.2
Char	63.6%	11.1	10.7	8.8	92.7	13.1	16.1	94.0	4.8

TABLE C-5 TRACE METAL BALANCE, TEST PERIOD 1 (ENGLISH)

Basis: 1 Day

	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	2.0	39.7	56.0	928.8	28.1	123.7	11.0	365.3	4.32
Sludge	.4	23.1	60.1	679.8	3.4	9.0	206.1	12.7	0.0
Total In	2.4	62.8	116.1	1608.6	31.5	132.7	217.1	378.0	4.32
Slag	.4	39.0	188.3	2409.0	5.2	52.6	118.3	19.9	.44
Char	.7	4.8	22.5	232.3	66.7	8.0	22.8	311.8	.02
Water *	-	-	-	-	-	-	-	-	-
Total Out	1.1	43.8	210.8	2641.3	71.9	60.6	141.1	331.7	.46

* No water sample taken during this period.

Percent of Total Out									
Slag	36.4	88.9	89.3	91.2	7.3	86.9	83.9	6.0	95.2
Char	63.6	11.1	10.7	8.8	92.7	13.1	16.1	94.0	4.8

The gas production and gas higher heating value for this period were 401.6 Nm^3 per Mg (13,600 Sft^3/ton) of total feed and 14.19 MJ per Nm^3 (360.4 Btu/Sft^3) respectively. These results were lower than the values determined for the refuse test period. Only one set of three gas samples was obtained during this test period, however, and the result may be in error. A gas particulate sample was not taken at this time so pitot tube data was not available for comparison. The gas production with sludge was within a standard deviation of the gas production observed during the refuse only test. The low heating value may be the result of sampling during low rate operation. The oxygen consumption was 0.17 Mg (tons) oxygen per Mg (ton) of combustible which was lower than that observed with refuse only. Effluent production was 0.363 cubic meters per Mg (87 gallons per ton) slightly higher than the refuse only result.

The trace metal balances obtained were similar to the balances which resulted from the refuse only tests. The amounts of copper and nickel entering the system were greater than with refuse only due to the high concentration of these metals in the sludge. No wastewater samples were taken during this period, so the metal balances do not include the wastewater stream. The fraction of each metal in the exiting streams is shown for comparison purposes.

The heat balance on the system is presented in Table C-6. The conversion efficiency based on heat leaving the process was 59.5 percent. This efficiency was lower than with refuse only. Lower efficiency was consistent with predicted system behavior due to the additional moisture added in the sludge. The low efficiency when compared to the refuse only test was caused by the lower gas production per Mg (ton) of feed. Heat contents of the other streams were similar to the refuse only result on a per Mg (ton) of material fed basis. The efficiency for the case of particulate recycle has been projected to be 75.1 percent.

TABLE C-6 PUROX SYSTEM HEAT BALANCE, TEST PERIOD 1

	GJ/Day	BTU x 10^{-6}/Day
Refuse*	960.5	910.4
Sludge	19.4	18.4
Fuel Gas	68.4	64.8
Oxygen	-	-
Total In	1048.3	993.6
Metal	-	-
PUROX System Gas	499.6	473.5
Slag	39.4	37.3
Char	75.0	71.1
Oil	64.6	61.2
Wastewater	44.3	42.0
Losses	116.2	110.1
Total Out	839.0	795.2
Δ	209.3	198.4

Efficiency (as operated) 59.5 percent
of Conversion (as projected) 75.1 percent

* Value is average for entire program. Efficiency based on total out.

APPENDIX D

TEST PERIOD 2. PRIMARY SLUDGE 27 APRIL - 30 APRIL 1977

The second test period processing 27.5 percent solids primary sludge at a dry sludge-to-refuse ratio of 0.036 was conducted between 27 - 30 April 1977. Heat and mass balances on the second sludge test period were also similar to those obtained during refuse only operation. The sludge fraction was slightly higher than during the first codisposal test, comprising 10 percent of the total feed. The methods used calculating these balances were identical to those used previously. The results are shown in Tables D-1 through D-6.

The gas production was 440 Nm^3 per Mg (14,900 Sft^3/ton) slightly higher than the refuse only case, and the standard deviation of the gas production from pitot tube data during steady operation was 52.3 Nm^3 per Mg (1772 Sft^3 per ton). Oxygen consumption was 0.19 Mg/Mg (tons/ton) of feed which fell between the values observed during the two test periods discussed earlier. Product gas heating value was 14.24 MJ per Nm^3 (361.6 Btu per standard cubic foot) lower than the refuse only result, and similar to the first sludge test.

Trace metal balances were also similar to those previously discussed. The effect of Huntington sludge was noticed again in the large quantities of copper and nickel exiting the process. The only significant difference between this period and previous tests was the lower fraction of total nickel entering which exited in the slag, 69 percent against 94 percent during other tests. However, 6.5 times as much nickel entered the process during this period than entered during the refuse only test. Additionally the nickel which exited the system was only 27 percent of the nickel which entered. Since the sludge contributed 96 percent of the entering nickel the total incoming nickel was reasonably accurate and the error is probably in the slag or char streams. The dilution of the wastewater by scrubber makeup rendered the wastewater metal content uncertain. The fraction of each metal in the exiting stream is shown for comparison purposes.

The heat balance for this test period resulted in a conversion efficiency of 61.9 percent, quite close to that obtained during refuse only operation. The heat content of all exit streams was nearly identical to other results when compared on a per unit of material fed basis. The efficiency projected for the case of particulate recycle was 76.8 percent.

TABLE D-1. MASS AND COMPONENT BALANCE, TEST PERIOD 2 (METRIC)

Basis: 1 Day

Stream	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse (As Received)	75.3						
(As Fed)		18.6	2.2	13.9	0.2	18.8	17.0
Sludge	7.3	0.5	0.1	0.4		5.4	1.1
Fuel Gas	1.2	0.9	0.3				
Oxygen	15.6			15.1			
Total In	99.4						
Metal	4.2						
PUROX Gas	42.5	16.1	1.8	23.3		0.8	
Slag	19.1	0.2		2.3			16.7
Char	3.4	1.9	0.1		0.1		1.4
Oil	1.6	1.3	0.2				
Wastewater	28.6	0.5	0.1	0.7	0.1	26.6	
Total Out	99.4						

TABLE D-2. MASS AND COMPONENT BALANCE, TEST PERIOD 2 (English)

Basis: 1 Day

Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse							
(as received)	83.0	-	-	-	-	-	-
(as fed)	-	20.5	2.4	15.3	.2	20.7	18.7
Sludge	8.1	.5	.1	.4	-	5.9	1.2
Fuel Gas	1.3	1.0	.3	-	-	-	-
Oxygen	17.2	-	-	16.7	-	-	-
Total In	109.6	-	-	-	-	-	-
Metal	4.6	-	-	-	-	-	-
PUROX Gas	46.9	17.7	2.0	25.7	-	.9	-
Slag	21.1	.2	-	2.5	-	-	18.4
Char	3.8	2.1	.1	-	.1	-	1.5
Oil	1.8	1.4	.2	.2	-	-	-
Wastewater	31.4	.6	.1	.8	.1	29.3	-
Total Out	109.6	-	-	-	-	-	-

TABLE D-3. AVERAGE PRODUCT GAS ANALYSIS, TEST PERIOD 2

	Mole Percent
H_2	29.62
CO	36.80
CH_4	5.02
C_2H_2	.41
C_2H_4	1.68
C_2H_6	.32
C_3H_6	.23
C_3H_8	.18
C_4	.34
C_5	.27
C_6H_6	.25
HHC	.29
H_2S	.04
CH_3OH	.08
CO_2	23.85
O_2	.03
Ar	.59

TABLE D-4. TRACE METAL BALANCE, TEST PERIOD 2 (Metric)

Basis: 1 Day

Stream	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	0.91	17.6	24.8	410.8	12.4	54.7	4.9	161.6	1.91
Sludge	0.54	15.6	53.3	368.9	2.1	5.9	127.1	6.9	0.06
Total In	1.45	33.2	78.1	779.7	14.5	60.6	172.0	168.5	1.97
Slag	0.18	12.4	78.5	1014.5	2.3	32.5	24.9	9.2	0.38
Char	0.32	2.2	10.2	105.4	30.2	3.6	10.3	141.4	0.01
Wastewater*	< 0.89	0.59	0.59	121.1	1.7	1.2	0.59	1.7	< 27.2
Total Out	0.40	14.6	88.7	1241.0	34.2	37.3	35.2	152.3	0.39
Percent Total Out									
Slag	36.4	84.9	88.5	81.7	6.7	87.1	70.7	6.0	97.4
Char	63.6	15.1	11.5	8.5	88.3	9.7	29.3	92.8	2.6
Wastewater	-	-	-	9.8	5.0	3.2	-	1.2	-

*Quantities of Cd and Hg are based on detection limits.

TABLE D-5. TRACE METAL BALANCE, TEST PERIOD 2 (English)

Basis: 1 Day

Stream	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	2.0	38.7	54.6	905.7	27.4	120.6	10.9	356.2	4.22
Sludge	1.2	34.3	117.6	813.2	4.6	13.1	280.3	15.2	.14
Total In	3.2	73.0	172.2	1718.9	32.0	133.7	291.2	371.4	4.36
Slag	.4	27.3	173.0	2236.6	5.1	71.7	54.9	20.2	.84
Char	.7	4.8	22.5	232.3	66.7	8.0	22.8	311.8	.02
Wastewater*	< 1.3	1.3	1.3	267.0	3.8	2.6	1.3	3.8	< 60
Total Out	1.1	32.1	195.5	2735.9	75.6	82.3	77.7	335.8	0.86
Percent of Total Out									
Slag	36.4	84.9	88.5	81.7	6.7	87.1	70.7	6.0	97.4
Char	63.6	15.1	11.5	8.5	88.3	9.7	29.3	92.8	2.6
Wastewater	-	-	-	9.8	5.0	3.2	-	1.2	-

*Quantities of Cd and Hg are based on detection limits.

TABLE D-6. PUROX SYSTEM HEAT BALANCE, TEST PERIOD 2

	GJ/Day	Btu x 10^{-6}/Day
Refuse*	953.5	903.7
Sludge	21.4	20.3
Fuel Gas	63.4	60.1
Oxygen	-	-
Total In	1038.3	984.1
Metal	-	-
PUROX System Gas	543.4	515.0
Slag	38.0	36.0
Char	75.0	71.1
Oil	64.6	61.2
Wastewater	44.3	42.0
Losses	113.2	107.3
Total Out	878.4	832.6
	159.8	151.5
Efficiency (as operated)	61.9 Percent	
Of Conversion (as projected)	76.8 Percent	

*Value is average for entire program. Efficiency based on total out.

APPENDIX E

TEST PERIOD 6. PRIMARY SLUDGE, 2 JUNE - 5 JUNE 1977

The third test period with 26.2% solids primary sludge at a dry sludge-to-refuse ratio of 0.024 took place between 2 and 5 June. This period of testing with primary sludge produced heat and mass balances with several differences from earlier results. The same techniques were used to calculate the balances. The wet sludge ratio during this test was 6 percent, the same ratio used during the first test, but the sludge had a higher moisture content. The balances are shown in Tables E-1 through E-6.

The trace metal balances obtained during this test were quite similar to those obtained during the refuse only test and earlier primary sludge tests. The distribution of metal among the three exit streams was essentially the same as the distribution measured during other tests despite the lower total slag rate. The dilution effect of the scrubber makeup water rendered the wastewater metal content uncertain. The fraction of each metal in the exiting streams is shown for comparison.

The slag production during this test was 0.18 Mg (ton) of slag per Mg (ton) of feed, much less than during other test periods. The lower slag production was indicative of a change in the composition of the incoming feed. Gas production was 490.2 Nm^3 per Mg (16,600 Sft^3 per ton), higher than previously measured, and oxygen-to-feed ratio was 0.21, also higher than previously measured. Pitot tube measurement of gas rate resulted in similar gas production result of 498.1 Nm^3 per Mg (16,866 Sft^3 per ton). The standard deviation of 12 gas production values obtained using pitot tube data was 38.5 Nm^3 per Mg (1302 Sft^3 per ton).

High gas production and oxygen consumption probably resulted from a change in refuse composition. The gas heating value was 14.11 MJ per Nm^3 (358.3 Btu per standard cubic foot), lower than previous results. Calculated wastewater production was 0.38 m^3 per Mg (100 gal/ton), which was higher than refuse-only results. The higher effluent production probably was caused by wetter sludge and refuse.

The heat balance, shown in Table E-6 differed from refuse results in the same manner as the mass balance. The heat content of the slag stream was lower, consistent with the lower slag production. The product gas contained more energy per ton of feed and more of the total exit energy than the refuse only result. This resulted in a conversion efficiency of 65.6 percent, despite the low gas heating value. The increase in efficiency was probably due to a change in incoming refuse rather than the effect of sludge processing. The efficiency with particulate recycle has been projected to be 74.8 percent.

TABLE E-1. MASS AND COMPONENT BALANCES, TEST PERIOD 6 (Metric)

Basis: 1 Day

Stream	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse (as received)	55.3	-	-	-	-	-	-
(as fed)	-	13.2	1.5	10.3	0.1	18.8	8.5
Sludge	3.4	0.3	-	0.1	-	2.4	0.5
Fuel Gas	1.7	1.4	0.3	-	-	-	-
Oxygen	12.9	-	-	-	-	-	-
Total In	73.3	-	-	-	-	-	-
Metal	2.5	-	-	-	-	-	-
PUROX System Gas	34.3	12.8	1.5	18.9	-	0.6	-
Slag	10.0	0.1	-	1.2	-	-	8.7
Char	0.9	0.5	-	-	-	-	0.4
Oil	1.2	1.0	0.1	0.1	-	-	-
Wastewater	24.4	0.5	0.1	0.6	0.1	23.1	-
Total Out	73.3	-	-	-	-	-	-

TABLE E-2. MASS AND COMPONENT BALANCES, TEST PERIOD 6 (English)

Basis: 1 Day

Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse							
(as received)	61.0	-	-	-	-	-	-
(as fed)	-	14.6	1.7	11.4	0.1	20.7	9.4
Sludge	3.7	0.3	-	0.1	-	2.7	0.6
Fuel Gas	1.9	1.5	0.4	-	-	-	-
Oxygen	14.2	-	-	13.7	-	-	-
Total In	80.8	-	-	-	-	-	-
Metal	2.8	-	-	-	-	-	-
PUROX Gas	37.8	14.1	1.6	20.8	-	0.7	-
Slag	11.0	0.1	-	1.3	-	-	9.6
Char	1.0	0.6	-	-	-	-	0.4
Oil	1.3	1.1	0.1	0.1	-	-	-
Wastewater	26.9	0.5	0.1	0.7	0.1	25.3	-
Total Out	80.8	-	-	-	-	-	-

TABLE E-3. AVERAGE PRODUCT GAS ANALYSIS, TEST PERIOD 6

	Mole Percent
H_2	29.94
CO	33.74
CH_4	5.89
C_2H_2	.52
C_2H_4	1.91
C_2H_6	.34
C_3H_6	.27
C_3H_8	.12
C_4	.28
C_5	.22
C_6H_6	.26
HHC	.17
H_2S	.02
CH_3OH	.04
CO_2	25.58
O_2	.04
Ar	.61

TABLE E-4. TRACE METAL BALANCE, TEST PERIOD 6 (Metric)

Basis: 1 Day

Stream	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	0.68	13.1	18.4	305.0	9.2	40.6	3.7	120.0	1.42
Sludge	0.09	2.0	4.2	67.7	0.4	0.6	19.6	0.9	0.0
Total In	0.77	15.1	22.6	672.7	9.6	41.2	23.3	120.9	1.42
Slag	0.05	33.9	33.9	1138.0	0.8	13.0	9.6	4.0	0.10
Char	0.09	0.6	2.7	27.8	7.9	1.0	2.7	37.2	0.03
Wastewater*	< 0.59	0.06	0.05	11.8	0.06	0.4	0.06	0.2	< 27.2
Total Out	0.14	34.5	36.65	1177.6	8.7	14.4	12.3	41.4	0.13
Percent Total Out									
Slag	33.0	98.3	92.5	96.6	9.2	90.3	78.0	9.7	76.9
Char	67.0	1.7	7.4	2.3	90.8	6.9	22.0	89.9	23.1
Wastewater	-	-	0.1	0.1	-	2.8	-	0.4	-

*Quantities of Cd and Hg are based on detection limits.

TABLE E-5. TRACE METAL BALANCE, TEST PERIOD 6 (English)

Basis: 1 Day

Stream	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	1.5	28.8	40.5	672.3	20.4	89.5	8.1	264.5	3.13
Sludge	0.2	4.4	9.2	149.3	0.9	1.4	43.3	1.9	0.00
Total In	1.7	33.2	49.7	826.1	21.3	90.9	51.4	266.4	3.13
Slag	0.1	74.8	74.8	2508.0	1.7	28.6	21.1	8.9	0.22
Char	0.2	1.3	6.0	61.2	17.5	2.2	6.0	82.0	0.07
Wastewater*	<1.3	0.13	0.1	26.1	0.13	0.9	0.13	0.5	<60
Total Out	0.3	76.1	80.9	2595.3	19.2	31.7	27.1	91.4	0.29
Percent Total Out									
Slag	33.0	98.3	92.5	96.6	9.2	90.3	78.0	9.7	76.9
Char	67.0	1.7	7.4	2.3	90.8	6.9	22.0	89.9	23.1
Wastewater	-	-	0.1	0.1	-	2.8	-	0.4	-

*Quantities of Cd and Hg are based on detection limits.

TABLE E-6. PUROX SYSTEM HEAT BALANCE, TEST PERIOD 6

	GJ/Day	Btu x 10^{-6}/Day
Refuse*	619.6	587.3
Sludge	10.7	10.1
Fuel Gas	92.7	87.9
Oxygen	-	-
Total In	723.0	685.3
Metal	-	-
PUROX System Gas	433.2	410.6
Slag	19.8	18.8
Char	19.7	18.7
Oil	46.6	44.2
Wastewater	38.4	36.4
Losses	102.9	97.5
Total Out	660.6	625.7
	62.4	59.6
Efficiency (as operated)	65.6 Percent	
Of Conversion (as projected)	74.8 Percent	

*Value is average for entire program. Efficiency based on Total Out.

APPENDIX F

TEST PERIOD 7. PRIMARY SLUDGE - JUNE 6-9, 1977

The final test with 22.3 percent solids primary sludge at a dry sludge-to-refuse ratio of 0.074 was conducted between 6 and 9 June. The test plan was to operate at a high rate with as high a sludge ratio as possible. The heat and mass balances calculated for the final period of primary sludge processing are shown in Tables F-1 through F-6. During this period, sludge was run at the highest rate which the feed system could handle, and contributed 23 percent of the total feed on a wet basis. The total converter rate during this test was 106.1 Mg (117 tons) per day, the highest during any test period.

Gas production was 395.7 Nm^3 per Mg (13,400 Sft^3 per ton), which was the lowest during any test period. The low gas production reflected the large quantity of water fed with the sludge. Pitot tube measurements resulted in a higher gas production of 524.5 Nm^3 per Mg (17,761 Sft^3 per ton) with a standard deviation of 78.3 (Nm^3 per Mg (2,651 Sft^3 per ton) for 12 samples. Oxygen-to-feed ratio was 0.18 which was within the range of oxygen consumption measurements determined for sludge processing and below that obtained during refuse only processing. Gas heating value was 15.10 MJ per Nm^3 (383.5 Btu per standard cubic foot), very close to the refuse only result.

The heating value was based on 15 samples which exhibited a standard deviation of 0.72 MJ per Nm^3 (18.3 Btu per standard cubic foot) was significantly higher than heating values determined during other primary sludge test periods. Slag production was 0.21 Mg (tons) per Mg (ton) of feed which was within the range of slag production observed during other tests. Effluent production was 0.405 cubic meters per Mg (107 gallons per ton) of feed which was higher than the refuse only result and other sludge processing results. The high effluent ratio was caused by the large quantity of sludge processed.

Trace metal balances obtained were similar to those determined for other periods. The nickel balance was quite poor, exiting nickel was only 11 percent of the incoming nickel. As earlier, the dilution of the wastewater by scrubber makeup rendered its metal content uncertain. Another difference was the relatively large amount of mercury found in the slag, which was much higher than during other periods. This finding was encouraging since the capture of significant amounts of mercury in the slag had not been observed earlier. The fraction of each metal in the exiting streams is shown for comparison.

The heat balance was similar to the results measured during earlier refuse only and codisposal tests. Higher production of char at the high operating rate resulted in a larger fraction of the total heat out being represented by the char stream. Also, the fraction of total heat out in the product gas stream was less than with refuse only reflecting the high total moisture content in the feed due to the increased wet sludge content. The conversion efficiency of the system for this period was 56.8 percent which was lowest of any period. The low efficiency was another result of the high moisture content of the sludge. High moisture resulted in lower gas production per unit of feed because it contributed nothing to the heating value of the gas, and it also increased the heat losses due to the large quantity of water which was heated and then condensed. The efficiency projected for the case of particulate recycle is 74.8 percent.

TABLE F-1. MASS AND COMPONENT BALANCES, TEST PERIOD 7 (METRIC)

Basis: 1 Day

Stream	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse							
(as received)	86.2	-	-	-	-	-	-
(as fed)		22.5	2.4	15.2	0.1	25.7	15.7
Sludge	20.1	1.2	0.3	0.4	0.1	15.6	2.5
Fuel Gas	1.7	1.4	0.3	-	-	-	-
Oxygen	19.1	-	-	18.5	-	-	-
Total In	127.1	-	-	-	-	-	-
Metal	4.1	-	-	-	-	-	-
PUROX Gas	49.4	19.0	2.1	26.9	-	0.9	-
Slag	18.0	0.1	2.0	-	-	-	15.9
Char	6.1	3.4	0.2	0.1	0.1	-	2.4
Oil	2.1	1.7	0.2	0.2	-	-	-
Wastewater	47.4	0.9	0.2	1.2	0.1	44.6	-
Total Out	127.1						

TABLE F-2. MASS AND COMPONENT BALANCES, TEST PERIOD 7 (ENGLISH)

Basis: 1 day

Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse							
(as received)	95.0	-	-	-	-	-	-
(as fed)	-	24.8	2.7	16.8	0.1	28.3	17.3
Sludge	22.2	1.3	0.3	0.4	0.1	17.2	2.8
Fuel Gas	1.9	1.5	0.4	-	-	-	-
Oxygen	21.0	-	-	20.4	-	-	-
Total In	140.1						
Metal	4.5	-	-	-	-	-	-
PUROX Gas	54.5	20.9	2.3	29.6	-	1.0	-
Slag	19.8	0.1	-	2.2	-	-	17.5
Char	6.7	3.7	0.2	0.1	0.1	-	2.6
Oil	2.3	1.9	0.2	0.2	-	-	-
Wastewater	52.3	1.0	0.2	1.3	0.1	49.2	-
Heat Loses	-	-	-	-	-	-	-
Total Out	140.1						

TABLE F-3. AVERAGE PRODUCT GAS ANALYSIS

Test Period 7

	Mole %
H_2	26.81
CO	34.19
CH_4	6.12
C_2H_2	0.72
C_2H_4	2.19
C_2H_6	0.40
C_3H_6	0.28
C_3H_8	0.19
C_4	0.40
C_5	0.36
C_6H_6	0.34
HHC	0.37
H_2S	0.03
CH_3OH	0.09
CO_2	26.85
O_2	0.04
Ar	0.63

TABLE F-4. TRACE METAL BALANCES, TEST PERIOD 7 (METRIC)

Basis: 1 day

Metal Stream	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	1.04	20.3	28.6	474.2	14.4	63.1	5.7	186.5	2.31
Sludge	2.36	57.4	27.5	1491.3	8.6	15.7	403.3	24.3	0.17
Total In	3.40	77.7	56.1	1965.5	23.0	78.8	409.0	210.8	2.38
Slag	0.09	61.1	59.3	1167.5	4.4	25.1	26.9	19.8	2.69
Char	0.54	3.9	18.0	185.8	53.2	6.4	18.2	249.4	0.18
Wastewater*	< 0.59	0.06	0.06	9.8	0.06	0.2	0.06	0.2	<27.2
Total Out	0.63	65.0	77.3	1363.1	57.6	31.7	45.1	269.4	2.87
Percent of Total Out									
Slag	14.3	94.0	76.7	85.7	7.6	79.2	59.6	7.3	93.7
Char	85.7	6.0	23.3	13.6	92.4	20.2	40.4	92.6	-
Wastewater	-	-	-	0.7	-	0.6	-	0.1	6.3

*Quantities of Cd and Hg are based on detection limits.

TABLE F-5. TRACE METAL BALANCE, TEST PERIOD 7 (ENGLISH)

Basis: 1 day

	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	2.3	44.7	63.0	1045.5	31.7	139.2	12.6	411.2	4.87
Sludge	5.2	126.5	60.7	3287.8	19.0	34.6	889.1	53.5	0.38
Total In	7.5	171.2	123.7	4333.3	50.7	173.8	901.7	464.7	5.25
Slag	0.2	134.6	130.7	2474.0	9.6	55.4	59.4	43.6	5.94
Char	1.2	8.7	39.7	409.7	117.3	14.2	40.2	549.8	0.40
Wastewater *	< 1.3	0.13	0.13	21.6	0.13	0.4	0.13	0.4	< 60.0
Total Out	1.4	143.3	170.4	3005.3	126.9	70.0	99.6	593.8	6.34
Percent of Total Out									
Slag	14.3	94.0	76.7	85.7	7.6	79.2	59.6	7.3	93.7
Char	85.7	6.0	23.3	13.6	92.4	20.2	40.4	92.6	-
Wastewater	-	-	-	0.7	-	0.6	-	0.1	6.3

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*Quantities of Cd and Hg are based on detection limits.

TABLE F-6. PUROX SYSTEM HEAT BALANCE, TEST PERIOD 7

	GJ/day	Btu x 10^{-6}/day
Refuse*	1027.8	974.2
Sludge	53.0	50.2
Fuel Gas	92.7	87.9
Oxygen	-	-
Total In	1173.5	1112.3
Metal	-	-
PUROX System Gas	637.8	604.5
Slag	35.7	33.8
Char	132.3	125.4
Oil	82.5	78.2
Wastewater	73.9	70.0
Losses	161.1	152.7
Total Out	1123.2	1064.6
Δ	60.3	47.7

Efficiency (as operated) 56.8%

Of Conversion (as projected) 74.8%

*Value is average for entire program. Efficiency based on total out.

APPENDIX G

TEST PERIOD 3. MIXED SLUDGE - 2 May - 5 May 1977

The first test of 21 percent solids mixed primary and secondary sludge at a dry sludge-to-refuse ratio of 0.049 was conducted between 2 and 5 May. The test began with the feeding of Pittsburgh sludge on May 2. The test was relatively free of mechanical breakdowns. High converter offgas temperature and low slag duct pressure, which are thought to be symptoms of bed channeling, were present during much of the period.

The first test of mixed sludge processing resulted in the balances shown in Tables G-1 through G-6. The most noticeable difference between this period and the refuse only period was the high oxygen consumption. The high measured oxygen consumption could have been the result of bed channeling during the test period. Channeling is believed to be caused by a deterioration in bed porosity due to poorly formed pellets of sludge and refuse. The PUROX System feeder has been specially designed to produce well formed pellets from shredded refuse over a range of moisture levels. However, if the moisture level of the feed is high and refuse and sludge are not uniformly blended, the pellets will be poorly formed. Poorly formed pellets can produce a variable porosity in the refuse bed leading to channeling with resultant inefficient heat transfer which produces high offgas temperatures and high oxygen consumption. The gas heating value was also affected. The heating value result of 12.78 MJ per Nm^3 (324.4 Btu/Sft^3 was much lower than the refuse only result and results during other codisposal periods. The standard deviation of the 9 heat value samples was 1.97 MJ per Nm^3 (50.1 Btu/Sft^3) which was much higher than other periods.

Gas production was slightly higher than with refuse only at 451.8 Nm^3 per/Mg (15,300 Sft^3 per ton) of feed. Effluent production was 0.467 cubic meters per Mg (112 gallons per ton) of feed which was high, and resulted from the high moisture content of the mixed sludge.

The trace metal balances were similar to those obtained for refuse only. The mixed sludge did not contain a major fraction of any incoming metal. As a result the incoming metal totals probably contain large errors due to the uncertainty in refuse composition. Because no char samples were collected during mixed sludge tests the char composition used to calculate the exiting nickel was that determined from char samples obtained during the refuse only test. This choice was made to prevent the char collected during primary sludge processing, which contained large concentrations of nickel, from causing errors in the balance. The distribution of metal among the exit streams was similar to the distribution observed for refuse only. The dilution of the wastewater by scrubber makeup water limited the detection of metals. The fraction of each metal in the exiting streams is shown for comparison purposes.

The system heat balance, shown in Table G-6, was similar to refuse only results. Losses per ton of feed were higher due to the high sludge moisture content and improper blending. Conversion efficiency was 58.7 percent, and was lower than the refuse only test result primarily due to the additional water processed. The conversion efficiency projected for particulate recycle was 71.2 percent.

TABLE G-1 MASS AND COMPONENT BALANCES, TEST PERIOD 3 (Metric)

Basis: 1 Day

STREAM	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse (as received)	61.1	-	-	-	-	-	-
(as fed)	-	14.5	1.6	8.7	-	21.9	11.4
Sludge	9.1	0.5	0.1	0.5	-	7.2	0.7
Fuel Gas	1.3	1.0	0.3	-	-	-	-
Oxygen	17.4	-	-	16.9	-	-	-
Total In	88.9	-	-	-	-	-	-
Metal	2.5	-	-	-	-	-	-
PUROX System Gas	37.4	13.2	1.5	21.2	-	0.6	-
Slag	12.7	0.0	-	1.4	-	-	11.3
Char	2.1	1.2	0.1	-	-	-	0.8
Oil	1.4	1.2	0.1	0.1	-	-	-
Wastewater	32.8	0.5	0.1	0.8	-	31.2	-
Total Out	88.9	-	-	-	-	-	-

TABLE G-2 MASS AND COMPONENT BALANCES, TEST PERIOD 3 (English)

Basis: 1 Day

Component Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse (as received)	67.3	-	-	-	-	-	-
(as fed)	-	16.0	1.8	9.6	-	24.1	12.6
Sludge	10.0	0.6	0.1	0.5	-	7.9	0.8
Fuel Gas	1.4	1.1	0.3	-	-	-	-
Oxygen	19.2	-	-	18.6	-	-	-
Total In	97.9	-	-	-	-	-	-
Metal	2.8	-	-	-	-	-	-
PUROX Gas	41.2	14.5	1.6	23.4	-	0.7	-
Slag	14.0	0.0	-	1.5	-	-	12.5
Char	2.3	1.3	0.1	-	-	-	0.9
Oil	1.5	1.3	0.1	0.1	-	-	-
Wastewater	36.1	0.6	0.1	0.9	-	34.4	-
Heat Losses	-	-	-	-	-	-	-
Total Out	97.9	-	-	-	-	-	-

TABLE G-3 AVERAGE PRODUCT GAS ANALYSIS, TEST PERIOD 3

	Mole Percent
H_2	30.32
CO	31.56
CH_4	4.82
C_2H_2	0.48
C_2H_4	0.68
C_2H_6	0.23
C_3H_6	0.20
C_3H_8	0.02
C_4	0.23
C_5	0.17
C_6H_6	0.22
HHC	0.12
H_2S	0.01
CH_3OH	0.12
CO_2	28.86
O_2	0.24
Ar	0.74

TABLE G-4 TRACE METAL BALANCE, TEST PERIOD 3 (Metric)

Basis: 1 Day

METAL STREAM	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	0.73	14.5	20.4	338.0	10.3	45.0	4.1	132.7	1.57
Sludge	0.59	2.3	7.8	234.1	2.6	3.8	0.7	21.4	0.11
Total In	1.32	16.8	28.2	572.1	12.9	48.8	4.8	154.4	1.69
Slag	0.14	3.8	48.3	673.1	1.6	17.8	1.9	5.8	0.13
Char	0.14	1.4	6.2	63.8	18.3	2.2	0.1	85.6	0.06
Wastewater *	<0.59	0.06	0.59	8.4	0.2	0.5	0.2	0.59	<27.2
Total Out	0.28	5.2	54.5	746.3	20.1	20.5	2.2	91.4	0.19
Percent of Total Out									
Slag	50.0	73.1	88.6	90.2	8.0	86.8	86.4	6.3	68.4
Char	50.0	26.9	11.4	8.5	91.0	10.7	4.5	93.7	31.6
Wastewater	-	-	-	1.3	1.0	2.5	9.1	-	-

*Quantities of Cd and Hg are based on detection limits.

TABLE G-5 TRACE METAL BALANCE, TEST PERIOD 3 (English)

Basis: 1 Day

	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb x 10^3)
Refuse	1.6	31.9	44.9	745.1	22.6	99.2	9.0	293.1	3.47
Sludge	1.3	5.0	17.1	516.0	5.7	8.3	1.6	47.2	0.25
Total In	2.9	26.9	62.0	1261.1	28.3	107.5	10.6	340.3	3.72
Slag	0.3	8.4	106.4	1484.0	3.6	39.2	4.1	12.8	.28
Char	0.3	3.0	13.7	140.7	40.3	4.8	0.3	188.7	.13
Wastewater *	< 1.3	0.13	1.3	18.5	0.4	1.2	0.5	1.3	<60
Total Out	0.6	11.5	120.1	1643.2	44.3	45.2	4.9	201.5	0.41
Percent of Total Out									
Slag	50	73.1	88.6	90.2	8.0	86.8	86.4	6.3	68.4
Char	50	26.9	11.4	8.5	91.0	10.7	4.5	93.7	31.6
Wastewater	-	-	-	1.3	1.0	2.5	9.1	-	-

*Quantities of Cd and Hg are based on detection limits.

TABLE G-6 PUROX SYSTEM HEAT BALANCE, TEST PERIOD 3

	GJ/Day	BTU x 10^{-6}/Day
Refuse*	667.5	632.7
Sludge	28.4	26.9
Fuel Gas	68.4	64.8
Oxygen	-	-
Total In	764.3	724.4
Metal	-	-
PUROX System Gas	419.6	397.7
Slag	25.2	23.9
Char	45.4	43.0
Oil	53.8	51.0
Wastewater	47.3	44.8
Losses	124.0	117.5
Total Out	715.2	677.9
Δ	49.1	46.5

Efficiency (as operated) 58.7 percent
of Conversion (as projected) 71.2 percent

*Value is average for entire test. Efficiency based on total out.

APPENDIX H

TEST PERIOD 4. MIXED SLUDGE - MAY 23-25, 1977

The final test using 20.3 percent solids mixed secondary and primary sludge at a dry sludge-to-refuse rate of 0.035 was conducted between 23 and 25 May. The heat and mass balances for this period are shown in Tables H-1 through H-6. Mixed primary and secondary sludge was processed at a rate of 10.5 Mg (11.6 tons) per day with 78.0 Mg (86.0 tons) of refuse for a wet sludge-to-refuse ratio of 0.135. The balances were calculated using the same methods for the refuse only case.

Mass balance results were similar to the results obtained during the refuse only test and quite different from the earlier mixed sludge test. Gas production was 395.7 Nm^3 per Mg (13,400 Sft^3 per ton) of feed; lower than the refuse only and earlier mixed sludge results. The oxygen-to-feed ratio of 0.18 was consistent with the refuse only and primary sludge results and much lower than the result for mixed sludge obtained during the 2 May - 6 May period. Product gas heating value was 15.22 MJ per Nm^3 (386.6 Btu/Sft^3), also consistent with refuse only results.

The trace metal distribution was similar to the results from the other test periods. The nickel contained in the char was again determined using the nickel concentration of the refuse-only char sample. The dilution of the wastewater by scrubber makeup limits wastewater metal content measurements. The fraction of each metal in the exiting streams is shown for comparison.

The heat balances on this period was consistent with previous balances. Losses were high due to the large quantity of water added by the sludge stream, and the conversion efficiency was 57.9 percent during the test. The efficiency projected for particulate recycle was 71.2 percent.

TABLE H-1. MASS AND COMPONENT BALANCE, TEST PERIOD 4 (METRIC)

Basis: 1 day

Stream	Total (Mg)	C (Mg)	H (Mg)	O (Mg)	S (Mg)	H_2O (Mg)	Ash (Mg)
Refuse							
(as received)	78.0	-	-	-	-	-	-
(as fed)	-	18.4	2.1	12.4	0.1	24.7	16.1
Sludge	10.5	0.7	0.1	0.4	-	8.3	0.8
Fuel Gas	1.7	1.4	0.3	-	-	-	-
Oxygen	16.1	-	-	15.5	-	-	-
Total In	106.3	-	-	-	-	-	-
Metal	3.8	-	-	-	-	-	-
PUROX Gas	41.8	15.9	1.7	22.3	-	0.7	-
Slag	17.2	0.2	-	1.7	-	-	15.3
Char	4.2	2.3	-	0.2	0.1	0.1	1.6
Oil	1.8	1.4	0.2	0.2	-	-	-
Wastewater	47.8	0.7	0.1	0.9	-	35.9	-
Total Out	106.3						

TABLE H-2. MASS AND COMPONENT BALANCES, TEST PERIOD 4 (ENGLISH)

Basis: 1 Day

Stream	Total (tons)	C (tons)	H (tons)	O (tons)	S (tons)	H_2O (tons)	Ash (tons)
Refuse							
(as Received)	86.0	-	-	-	-	-	-
(as fed)		20.3	2.3	13.7	0.1	27.2	17.8
Sludge	11.6	0.8	0.1	0.4	-	9.2	0.9
Fuel Gas	1.9	1.5	0.4	-	-	-	-
Oxygen	17.7	-	-	17.1	-	-	-
Total In	117.2	-	-	-	-	-	-
Metal	4.2	-	-	-	-	-	-
PUROX Gas	45.7	17.5	1.9	24.6	-	0.8	-
Slag	19.0	0.2	-	1.9	-	-	16.9
Char	4.6	2.5	0.2	-	0.1	-	1.8
Oil	2.0	1.6	0.2	0.2	-	-	-
Wastewater	41.7	0.8	0.1	1.0	-	39.6	-
Heat Losses	-	-	-	-	-	-	-
Total Out	117.2						

TABLE H-3. AVERAGE PRODUCT GAS ANALYSIS, TEST PERIOD 4

	Mole %
H_2	25.30
CO	36.72
CH_4	6.48
C_2H_2	0.60
C_2H_4	2.26
C_2H_6	0.46
C_3H_6	0.39
C_3H_8	0.21
C_4	0.44
C_5	0.31
C_6H_6	0.26
HHC	0.23
H_2S	0.02
CH_3OH	0.11
CO_2	25.01
O_2	0.26
Ar	0.95

TABLE H-4. TRACE METAL BALANCE, TEST PERIOD 4 (METRIC)

Basis: 1 day

Metal Stream	Cd (kg)	Cr (kg)	Cu (kg)	Fe (kg)	Pb (kg)	Mn (kg)	Ni (kg)	Zn (kg)	Hg (g)
Refuse	1.00	19.3	27.2	450.6	13.7	60.0	5.4	177.3	2.10
Sludge	0.50	6.6	0.0	307.9	7.5	5.6	0.7	35.2	0.19
Total In	1.50	25.9	27.2	758.5	21.2	65.6	6.1	212.4	2.29
Slag	0.09	58.6	49.4	844.6	1.9	19.7	3.4	6.0	0.86
Char	0.36	2.7	12.4	127.6	36.6	4.4	0.4	171.2	0.12
Wastewater*	< 0.59	0.06	0.2	8.4	0.2	0.3	0.0	0.6	< 27.2
Total Out	0.45	61.3	62.0	980.6	38.7	24.4	3.8	177.8	0.98
Percent of Total Out									
Slag	20.0	95.6	79.7	86.1	5.9	80.7	89.5	3.4	87.8
Char	80.0	4.4	20.0	13.0	94.6	18.0	10.5	96.3	12.2
Wastewater	-	-	0.3	0.9	0.5	1.3	-	0.3	-

*Quantities of Cd and Hg are based on detection limits.

TABLE H-5. TRACE METAL BALANCE, TEST PERIOD 4 (ENGLISH)

Basis: 1 day

	Cd (lb)	Cr (lb)	Cu (lb)	Fe (lb)	Pb (lb)	Mn (lb)	Ni (lb)	Zn (lb)	Hg (lb)
Refuse	2.2	42.5	59.9	993.5	30.1	132.3	12.0	390.8	4.63
Sludge	1.1	14.5	-	678.8	16.5	12.3	1.5	77.5	0.42
Total In	3.3	67.0	59.9	1672.3	46.6	144.6	13.5	468.3	5.05
Slag	0.2	129.2	109.0	1862.0	4.1	43.4	7.6	13.2	1.90
Char	0.8	6.0	27.3	281.2	80.7	9.7	0.8	377.5	0.27
Wastewater *	<1.3	0.13	0.5	18.5	0.5	0.6	0.1	1.3	<60.0
Total Out	1.0	135.2	136.8	2161.7	85.3	53.7	8.5	392.0	2.17
Percent of Total Out									
Slag	20.0	95.6	79.7	86.1	5.9	80.7	89.5	3.4	87.8
Char	80.0	4.4	20.0	13.0	94.6	18.0	10.5	96.3	12.2
Wastewater	-	-	0.3	0.9	0.5	1.3	-	0.3	-

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*Quantities of Cd and Hg are based on detection limits.

TABLE H-6. PUROX SYSTEM HEAT BALANCE, TEST PERIOD 4

	GJ/Day	Btu x 10^{-6}/day
Refuse*	902.2	855.1
Sludge	33.6	31.8
Fuel Gas	92.7	87.9
Oxygen	-	-
Total In	1028.5	974.8
Metal	-	-
PUROX Gas	535.5	507.6
Slag	34.2	32.4
Char	90.8	86.1
Oil	71.7	68.0
Wastewater	56.1	53.2
Losses	136.8	129.7
Total Out	925.1	877.0
Δ	103.4	97.8
Efficiency (as operated) 57.9%		
Of Conversion (as projected) 71.2%		

*Value is average for entire program. Efficiency based on total out.